DOCTORAL THESIS

DIGITAL ECOSYSTEM FOR ADDITIVE MANUFACTURING DRIVEN BY STANDARDS-BASED DIGITAL THREAD AND DIGITAL TWIN

ECOSSISTEMA DIGITAL PARA MANUFATURA ADITIVA HABILITADO POR CADEIA DIGITAL E GÊMEO DIGITAL BASEADOS EM PADRÕES

EFRAIN ANDRES RODRIGUEZ GASCA

Brasilia, December 2024

UNIVERSITY OF BRASILIA

FACULTY OF TECHNOLOGY

UNIVERSITY OF BRASILIA
FACULTY OF TECHNOLOGY
DEPARTMENT OF MECHANICAL ENGINEERING

DIGITAL ECOSYSTEM FOR ADDITIVE MANUFACTURING DRIVEN BY STANDARDS-BASED DIGITAL THREAD AND DIGITAL TWIN

EFRAIN ANDRES RODRIGUEZ GASCA

DOCUMENT SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING AT THE TECHNOLOGY FACULTY OF THE UNIVERSITY OF BRASILIA AS PART OF THE NECESSARY REQUIREMENTS FOR OBTAINING THE DEGREE OF DOCTOR OF MECHATRONIC SYSTEMS

APPROVED BY:

Prof. Dr. Alberto J. Alvares, PPMEC/UnB
Advisor

Prof. Dr. Maksym Ziberov, ENM/UnB
Internal Member

Prof. Dr. Adriano Fagali de Souza, Engenharia Mecânica/UFSC
External Member

Prof. Dr. João Carlos Espíndola Ferreira, Engenharia Mecânica/UFSC
External Member

BRASILIA/DF, December 2024

Rodriguez, Efrain. Digital Ecosystem for Additive Manufacturing Driven by Standards-based Digital Thread and Digital Twin . –Brazil, 2024.
Advisor: Alberto José Alvares

Doctoral Thesis – University of Brasilia – UnB
Faculty of Technology – FT
Programa de Pós-Graduação em Sistemas Mecatrônicos – PPMEC, 2024.

1. Additive Manufacturing 2. Digital Thread 3. Digital Twins 4. Industry 4.0 5. Digital Ecosystem

Dedication

A mis padres Julia y Walter (en su memoria).
A mi tío Efrain (en su memoria).
A mi hijo Thiago.
A Killua y Bella (en su memoria), mis compañeros en tantas noches de desvelo mientras escribía este documento.

EFRAIN ANDRES RODRIGUEZ GASCA

Acknowledgements

Primero agradezco a Dios por darme licencia, sabiduría y entendimiento para alcanzar este logro.
Le agradezco a mis padres por todo el amor y el apoyo que siempre me han brindado. Les doy gracias por todo el sacrificio que hicieron para impulsarme. Este logro es por ustedes. Y a ti viejo, si desde el cielo me ves, espero aún estés orgulloso. Gracias!
Les agradezco a mis hermanos Juanpa, Nany y Lole por el apoyo incondicional y las palabras de aliento que me han dado cuando las necesito. Gracias Juanpa por brindarme soporte en esos momentos difíciles. También, gracias por las ideas que me ayudaron a resolver algunos de los enredos de este trabajo de tesis.
Quiero agradecer especialmente a Michell Posada, mi compañera y amiga, quien ha estado para mi en esos momentos de dificultades, motivandome a seguir adelante y recordandome que puedo alcanzar lo que me propongo. Le doy gracias por toda la paciencia y el apoyo incondicionales a lo largo de esta etapa.
Gracias a mi hijo Thiago, aunque él no lo entiende aún, se ha convertido en una fuente de motivación para sacar este doctorado adelante.
Gracias a Killua y Bella por enseñarme de lealtad verdadera y por la compañía a pesar de las noches frias a mi lado en el escritorio.
Le agradezco al admirable profesor Alberto Alvares por compartir de su conocimiento conmigo guiando este trabajo tesis. También por la confianza, la paciencia y el apoyo que me brindó a lo largo del doctorado.
Finalmente, una enorme gratitud con el CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) por el financiamiento y con el PPMEC (Programa de Pós-Graduação em Sistemas Mecatrônicos)/UnB por disponibilizar sus recursos físicos (laboratórios, máquinas y herramientas) para el desarrollo de este trabajo.

EFRAIN ANDRES RODRIGUEZ GASCA

Abstract

In modern manufacturing systems, the integration of Digital Thread (DTh) and Digital Twin (DTw) technologies has emerged as a cornerstone for achieving seamless orchestration across the entire product lifecycle. These technologies have the potential to revolutionize manufacturing by enabling enhanced connectivity, real-time monitoring, and advanced decision making. This work proposes a digital ecosystem framework grounded in standards-based DTh and DTw technologies, with STEP-NC at its core. Building on the ISO 23247 framework, the ecosystem integrates key open standards like STEP, STEP-NC, MTConnect, OPC-UA, MQTT and QIF, enabling interoperability and contextual data exchange across the manufacturing lifecycle. STEP-NC enriches this ecosystem by providing detailed contextual data about products, processes, and machines, fostering the development of DTw for virtual monitoring, optimization, and informed decision-making. To validate the proposed digital ecosystem, several implementation scenarios were developed. A robotic machining scenario demonstrated the adaptability of STEP-NC for programming and simulating machining operations on an ASEA robotic arm, showcasing its potential while identifying areas for refinement. For additive manufacturing (AM), STEP-NC was adapted for Fused Deposition Modeling (FDM), enabling toolpath simulation with a 3D virtual model of a RepRap 3D printer, while MTConnect provided real-time monitoring of extrusion parameters and build progress. The simulation of robotic Laser Metal Deposition (LMD) toolpaths using a Kuka KR70 robot underscored STEP-NC capability to support complex metal AM processes, emphasizing the importance of integrating AM-specific kinematic models for realistic toolpath verification. Additionally, new EXPRESS-based STEP-NC models were proposed for FDM and LMD, addressing process-specific parameters and advancing standardization efforts. Finally, a TypeScript-based STEP-NC library was developed to facilitate model serialization and web-based integration, although future automation of TypeScript class generation from EXPRESS models remains essential. In conclusion, this thesis contributes significantly to advancing STEP-NC within a comprehensive digital ecosystem, while the developed implementation scenarios underline its potential and identifies areas for further refinement and adoption.

Resumo

Nos sistemas modernos de manufatura, a integração das tecnologias de Digital Thread (DTh) e Digital Twin (DTw) tornou-se um pilar essencial para alcançar uma orquestração fluida de dados ao longo do ciclo de vida do produto. Essas tecnologias têm o potencial de revolucionar a manufatura, permitindo conectividade aprimorada, monitoramento em tempo real e tomada de decisões avançada. Este trabalho propõe uma estrutura de ecossistema digital baseada em tecnologias de DTh e DTw fundamentadas em padrões, tendo o STEP-NC como padrão central. Com base na interface estrutural da ISO 23247, o ecossistema integra padrões abertos fundamentais como STEP, STEP-NC, MTConnect, OPC-UA, MQTT e QIF, permitindo interoperabilidade e troca de dados contextualizaos ao longo do ciclo de vida daos procesos de manufatura. O STEP-NC enriquece o ecossistema com dados contextuais detalhados sobre produtos, processos e máquinas, promovendo o desenvolvimento de DTw para monitoramento virtual, otimização e tomadas de decisão informadas. Para validar o ecossistema digital proposto, diversos cenários de implementação foram desenvolvidos. Um cenário de usinagem robótizada demonstrou a adaptabilidade do STEP-NC para programar e simular operações de usinagem com um robô industrial ASEA, evidenciando seu potencial enquanto foram identificadas áreas para refinamento. Para a manufatura aditiva, o STEP-NC foi adaptado para o processo de FDM, permitindo a simulação de trajetórias de deposição com um modelo virtual 3D de uma impressora 3D RepRap. Complementarmente, o MTConnect foi utilizado para estabelecer um sistema de monitoramento em tempo real, fornecendo informações detalhadas sobre os parâmetros de extrusão e o progresso da construção. A simulação de trajetórias de ferramenta para Deposição de Metal a Laser (LMD) utilizando um robô Kuka KR70 destacou a capacidade do STEP-NC em suportar processos complexos de AM com metais, enfatizando a importância da integração de modelos cinemáticos do robô para uma validação realista das trajetórias de deposição. Além disso, novos modelos de STEP-NC em EXPRESS foram propostos para FDM e LMD, abordando parâmetros específicos dos processos e avançando nos esforços de padronização. Esses modelos aprimoram significativamente a representação das tecnologias dentro da norma STEP-NC, oferecendo um caminho para uma adoção mais ampla. Por fim, foi desenvolvida uma biblioteca STEP-NC baseada em TypeScript para facilitar a serialização de modelos e a integração baseada na web, embora a automação futura da geração de classes TypeScript a partir de modelos EXPRESS permaneça uma área essencial de trabalho. Em conclusão, esta tese contribui significativamente para o avanço

do STEP-NC como um elemento central de um ecossistema digital abrangente. O framework proposto e os cenários de implementação desenvolvidos ressaltam seu potencial transformador, ao mesmo tempo em que identificam áreas críticas para pesquisas futuras e refinamentos visando sua adoção plena na manufatura moderna.

Summary

Abstract ... **i**

Abstract ... **ii**

List of figures ... **vi**

List of tables ... **x**

1 Introduction ... **1**

1.1 Contextualization ... 1
1.2 Research problem: definition and motivation ... 5
1.2.1 Research question ... 9
1.2.2 Hypothesis to test ... 9
1.3 Objectives ... 9
1.3.1 Specific objectives ... 10
1.4 Contributions ... 10
1.5 Document organization ... 12

2 Theoretical background ... **14**

2.1 Industry 4.0 ... 14
2.1.1 Reference Architecture Model for Industry 4.0 (RAMI 4.0) ... 16
2.2 Smart Manufacturing (SM) ... 18
2.3 Cyber-Physical Systems (CPS) ... 22
2.3.1 Cyber-Physical Production Systems (CPPS) ... 23
2.4 Internet of Things (IoT) ... 25
2.4.1 Industrial Internet of Things (IIoT) ... 27
2.4.1.1 Industrial Internet of Things Reference Architecture (IIRA) ... 27
2.5 Enabling standard technologies and frameworks ... 28
2.5.0.1 ISO 23704 - Cyber-physically controlled smart machine tool systems ... 31
2.6 Communication protocols ... 32
2.6.1 MTConnect ... 32
2.6.2 OPC-UA ... 33

2.6.3 MQTT 34
2.7 Manufacturing processes 35
2.8 Additive Manufacturing (AM) 36
2.8.1 Primary AM application areas 37
2.8.2 Classification of AM processes. 38

3 Digital Thread for Additive Manufacturing: Literature Review 42
3.1 Product Lifecycle Management (PLM) 42
3.2 Digital Thread (DTh) 44
3.3 Research on Digital Thread in AM 46
3.3.1 Data models and file formats for DTh in AM 51
3.3.1.1 STL format 51
3.3.1.2 AMF format 53
3.3.1.3 3MF format 53
3.3.1.4 OBJ format 54
3.3.2 CLI format 54
3.3.3 The need for a high-level data format to support the AM DTh. 54

4 Digital Twins for Additive Manufacturing: Literature Review 57
4.1 Digital Twins (DTw) concept 57
4.1.1 Characterization of the DTw 58
4.1.2 Reference models of DTw for manufacturing 60
4.1.2.1 Three-dimensional model 61
4.1.2.2 Five-dimensional model 62
4.1.2.3 Digital twin framework for machining 62
4.1.2.4 Other related proposals 63
4.1.2.5 The ISO 23247 DTw framework for manufacturing 63
4.1.2.6 Research on ISO 23247 framework 65
4.2 Research on DTw in AM processes 66

5 STEP-NC as a Method for Integrating Contextualized Data in a Digital AM Ecosystem 73
5.0.1 Overview of the STEP and STEP-NC standards 73
5.0.1.1 Description method EXPRESS 74
5.0.1.2 Implementation methods 75
5.0.1.3 Part 21 - Clear text encoding of exchange structure 76
5.0.1.4 Application Protocols (APs) 78
5.0.1.5 STEP modeling types 78
5.0.2 STEP-NC 79
5.1 Overview of the current STEP-NC data model for AM 80

5.2 Methodological Framework for the Literature Review 84
5.3 Research review on STEP-NC in AM processes 86
5.3.1 STEP-NC data models and implementations in AM 89
5.4 Short Survey on STEP-NC Implementation Architectures............................ 93

6 Towards a Digital Ecosystem for AM driven by Standards-based Digital Thread and Digital Twins. 97
6.1 Unified digital ecosystem for contextualized intelligence............................. 97
6.1.1 Contextualized data storage... 99
6.1.2 Challenges of the proposed unified ecosystem.. 100
6.2 Proposal of a digital ecosystem for AM driven by standards-based DTh and DTw 101
6.2.1 Benefits and Challenges of the Proposed Ecosystem 106

7 Practical Implementations 108
7.1 Scenario 1: STEP-NC implementation method for industrial robotic machining 108
7.2 Scenario 2: Implementation of STEP-NC and MTConnect in AM using an FDM process 112
7.3 Scenario 3: Simulation of the STEP-NC program for the robotic LMD process . 122
7.4 Scenario 4: EXPRESS modeling of STEP-NC data entities for FDM and LMD processes 124
7.5 Scenario 5: Development of a new software library to handle STEP-NC programs 131

8 Conclusions 139
8.1 Conclusions.. 139
8.1.1 Conclusion from the literature review on DTh in AM (Chapter 3).................. 139
8.1.2 Conclusion from the literature review on DTw in AM (Chapter 4) 140
8.1.3 Conclusion from literature review on STEP-NC in AM (Chapter 5) 141
8.1.4 Conclusions from the proposed digital ecosystem (Chapter 6) 141
8.1.5 Conclusions from the implementation scenarios (Chapter 7) 142
8.2 Summary of final contributions of this thesis.. 144
8.3 Future directions.. 145

REFERÊNCIAS BIBLIOGRÁFICAS 148

A Appendix 183
A.1 Journal research publications.. 183

B Appendix 193
B.1 Guide: how to use the stepnc.dll to generate STEP-NC programs 193

List of figures

1.1 Stages of manufacturing automation throughout the digital evolution. Font: Author 2

2.1 The four stages of the Industrial Revolution. Adapted from [18] ... 15
2.2 Reference architecture model for Industry 4.0 (RAMI4.0) [87] ... 17
2.3 Conceptual framework for Industry 4.0 smart manufacturing systems proposed in reference [20] ... 20
2.4 NIST's conceptualization of a ecosystem for SM [96]. ... 21
2.5 3-tiers architecture of service-based CPS [106]. ... 22
2.6 Decentralizing the traditional automation pyramid: A breakdown of the automation hierarchy through distributed services [34] ... 24
2.7 Fundamental IoT architectures: (A) Three layers; (B) Five layers. [122]. ... 26
2.8 Industrial Internet of Things Reference Architecture (IIRA) [125] ... 28
2.9 Chronological representation of standards across various stages in the product lifecycle [37, 127]. ... 29
2.10 Overall structure of the ISO 23704 [138]. ... 31
2.11 A typical data flow in MTConnect-based communication [146] ... 33
2.12 Basic OPC UA communication structure ... 34
2.13 Typical MQTT publisher/subscriber architecture. Adapted form [148] ... 35
2.14 Production domains of the AM processes. ... 38
2.15 Overview of AM technology categories. ... 39
2.16 Directed Energy Deposition (DED) [169] ... 39
2.17 Meltio's wire-laser 3D print system for LDM ... 40
2.18 Material Extrusion (MEX) [169] ... 41

3.1 PLM and and DTh through product life cycle. Adapted from [175]. ... 43
3.2 The vision of DTh from the NIST SMS Test Bed [189]. ... 45
3.3 Integration of engineering design within the product lifecycle using the DTh [192]. 46
3.4 Publications by year on Digital Thread in AM using the query TITLE-ABS-KEY ((“additive manufacturing” OR “3D printing” OR “rapid prototyping”) AND (“Digital Thread” OR “Digital Chain”)) ... 47
3.5 Additional statistics from the Scopus database regarding DTh in AM: (a) Documents by country; (b) Documents by affiliation. ... 48

3.6 Overview of the AM Digital Thread. Adapted from [183, 186, 197] 49
3.7 NIST's federated information systems architecture for AM [183] 56

4.1 Characterization of DTw according to its data integration level [220] 60
4.2 Three-dimensional reference models of Digital Twin: a) adapted from [216]; b) adapted from [37] 62
4.3 Digital Twin framework for machining proposed by STEP Tools, Inc. [54]. 63
4.4 DTw framework for manufacturing from ISO 23247 Part 2 [232] 65
4.5 Publications by year on Digital Twin in AM using the query TITLE-ABS-KEY ((“additive manufacturing” OR “3D printing” OR “rapid prototyping”) AND (“Digital Twin”)). 67
4.6 Publications by year on Digital Twin in AM using the query TITLE-ABS-KEY ((“additive manufacturing” OR “3D printing” OR “rapid prototyping”) AND (“Digital Twin”)). 68

5.1 Example EXPRESS-G diagram [274] 76
5.2 Part 21 file example 77
5.3 Overview of the ISO 10303 AP242 [127] 79
5.4 Overview of the structure of STEP-NC. 81
5.5 Current AM data entities mapped from ISO 14649 to the AP238 [295]. 83
5.6 Literature review methodology. 85
5.7 Documents by year: (a) Publications on STEP-NC overall using the query TITLE-ABS-KEY ("STEP-NC" OR "ISO 14649" OR "ISO 10303-238" OR "AP238"); (b) Publications on STEP-NC in AM using the query TITLE-ABS-KEY (("additive manufacturing" OR "3D printing" OR "rapid prototyping") AND ("STEP-NC" OR "ISO 14649" OR "ISO 10303-238" OR "AP238")). 87
5.8 Additional statistics from the Scopus database regarding STEP-NC in AM (TITLE-ABS-KEY (("additive manufacturing" OR "3D printing" OR "rapid prototyping") AND ("STEP-NC" OR "ISO 14649" OR "ISO 10303-238" OR "AP238"))): (a) Documents by country; (b) Documents by affiliation. 88
5.9 STEP-NC architectures in literature: a) Indirect; b) Interpreted; c) Adaptive; d) Hybrid; e) Collaborative. 96

6.1 Concept of an AM Digital Thread connected with Digital Twins. 98
6.2 Concept of Multi-Threaded data flow interconnected with Digital Twins for cross-context lifecycle analysis. 99
6.3 Digital ecosystem framework for AM driven by standards-based Digital Thread and Digital Twin. 102

7.1 IDEF0 activities diagram for the scenario 1 109

7.2 Workflow for generating a STEP-NC file from Mastercam machining data using an adapter. 110
7.3 Overview of the robotic machining DTh. 111
7.4 STEP-NC and MTConnect implementations in AM through digital ecosystem framework. 113
7.5 Overview of the DTh of the FDM AM process. 114
7.6 Part model sliced into an XML layer file. 114
7.7 AM STEP-NC program and layers visualization in STEP-NC Machine software. .. 116
7.8 Configuring the 3D printer kinematic model into the STEP-NC Machine software. 117
7.9 Simulation of the AM STEP-NC program with machine 3D model in the STEP-NC machine software. 118
7.10 MTConnect implementation: a) Architecture; b) 3D printer machine model. 119
7.11 MTConnect XML response for "current" request with machine operating. 120
7.12 MTConnect web client for AM process monitoring. 121
7.13 STEP-NC toolpath simulation for LMD process. 123
7.14 Overview of the DTh of the LMD AM process. 124
7.15 EXPRESS-G diagram of the proposed am_deposition_operation entity. 126
7.16 EXPRESS-G diagram of the proposed am_fdm_technology entity. 128
7.17 EXPRESS-G diagram of the proposed am_lmd_technology entity. 129
7.18 EXPRESS-G diagram of the proposed am_machine_functions entity. 130
7.19 Technology stack used to build the STEP-NC library. 133
7.20 Structure of the STEP-NC library. 133
7.21 Typescript code snippet showing a entity class created inside the library. 135
7.22 Example of P21 file generated with the STEP-NC library. 136
7.23 JSON response from local server using the STEP-NC library. 138

A.1 Article 1 (Under Review in IJAMT Journal): STEP-NC in Additive Manufacturing: A Comprehensive Review, Architecture and Data Model Proposal 183
A.2 Article 2: A STEP-NC implementation approach for additive manufacturing 184
A.3 Article 3: Developing a MTConnect Framework for RepRap Additive Manufacturing Machines 185
A.4 Article 4: Modelo de información para manufactura aditiva basado en STEP-NC ... 186
A.5 Article 5: STEP-NC Architectures for Industrial Robotic Machining: Review, Implementation and Validation 187
A.6 Article 6: Digital Twin Implementation for Machining Center Based on ISO 23247 Standard 188
A.7 Article 7: Expert system to implement STEP-NC data interface model on CNC machine 189
A.8 Article 8: A Closed-Loop Inspection Architecture for Additive Manufacturing Based on STEP Standard 190

A.9 Article 9: New system architecture and algorithm design for indirect STEP-NC implementation…… 191
A.10 Article 10: STEP-NC-based machining architecture applied to industrial robots …. 192

List of tables

1.1 Research works focused on the integration of DTh and DTw. 7

2.1 Design principles associated to each Industry 4.0 component [86]. 15
2.2 Wireless communication protocols with associated parameters. Adapted from [121]. 30

3.1 Summary of Digital Thread proposals for AM. 52

4.1 Characteristics of the DTw and their descriptions. 59
4.2 Comparison of Digital Thread and Digital Twin. 61
4.3 Overview of DTw applications in AM 72

5.1 Organization of Parts within the STEP standards series 74
5.2 Comparisons between an ISO 14649 (ARM) and ISO 10303-238 (AIM) model [285]. 80
5.3 Summary of reviewed research works on STEP-NC in AM processes. 94

6.1 Key standards for the proposed digital ecosystem. 104

7.1 Key requirements for the proposed STEP-NC library 131

8.1 Breakdown of references reviewed in this thesis 140

List of symbols and abbreviations

3MF 3D Manufacturing Format

AI Artificial Intelligence

AM Additive Manufacturing

AMF Additive Manufacturing File

BDA Big-Data Analytics

CAD Computer-Aided Design

CAI Computer-Aided Inspection

CAIP Computer-Aided Inspection Planning

CAM Computer-Aided Manufacturing

CAPP Computer-Aided Process Planning

CAx Computer-Aided Technologies

CC Cloud Computing

CMM Coordinate Measuring Machines

CNC Computer Numerical Control

COMAC Commercial Aircraft Corporation of China, Ltd.

CPPS Cyber-Physical Production Systems

CPS Cyber-Physical Systems

DTh Digital Thread

DTw Digital Twins

FDM Fused Deposition Modeling

HTTP HyperText Transfer Protocol

ICT Information and Communication Technologies

IIoT Industrial Internet of Things

IIRA Industrial Internet of Things Reference Architecture

IoS Internet of Services

IoT Internet of Things

IT Information Technologies

LMD Laser Metal Deposition

MQTT Message Queuing Telemetry Transport

NC Numerical Control

NIST National Institute of Standards and Technology

OPC UA OPC Unified Architecture

PLM Product Lifecycle Management

RAMI 4.0 Reference Architecture Model for Industry 4.0

SM Smart Manufacturing

STEP Standard for the Exchange of Product Data

STEP-NC Standard for the Exchange of Product Data - Numerical Control

STL Standard Tessellation Language

XML Extensible Markup Language

Chapter 1

Introduction

1.1 Contextualization

In today's fast-paced and increasingly interconnected world, digitalization has emerged as a transformative force, changing not only how people live but also the socio-economic and industrial sphere worldwide [1]. Digitalization can be referred to as the "integration of digital technologies into everyday life by the digitization of everything that can be digitized", according to the Business Dictionary (2015) [2]. However, this digital transformation goes beyond just digitizing analog processes (digital enablement) or improving existing digital ones (digital optimization) [3]. It represents a complete paradigm shift that uses cutting-edge digital technologies to generate value for new products/processes, organizations, and businesses [4]. By embracing this transformation, modern companies can unlock new sources of revenue, improve profitability, and create innovative opportunities to better serve their customers in a wide range of sectors [5], including the manufacturing industry.

The manufacturing industry, in particular, has been profoundly shaped by ongoing digital transformation since the advent of the first computers in the mid-20th century. This digital evolution has unfolded through four disruptive stages of manufacturing automation, each catalyzing significant levels of advancement, as depicted in Figure 1.1.

The first stage, machine-level automation (1940-1950), marked a significant milestone in the digital enablement of machine tools. They evolved from being solely dependent on the human operator to integrating motorized axes guided by NC (Numerical Control [6]) programs, recorded on punched tapes/cards and drum memories. This groundbreaking development significantly reduced the need for human intervention and resulted in a substantial improvement in the quality of fabricated parts [7].

The second stage, system-level automation (1960-1980), emerged with rapid progress in the processing power and storage capacity of computers. This digital advancement paved the way

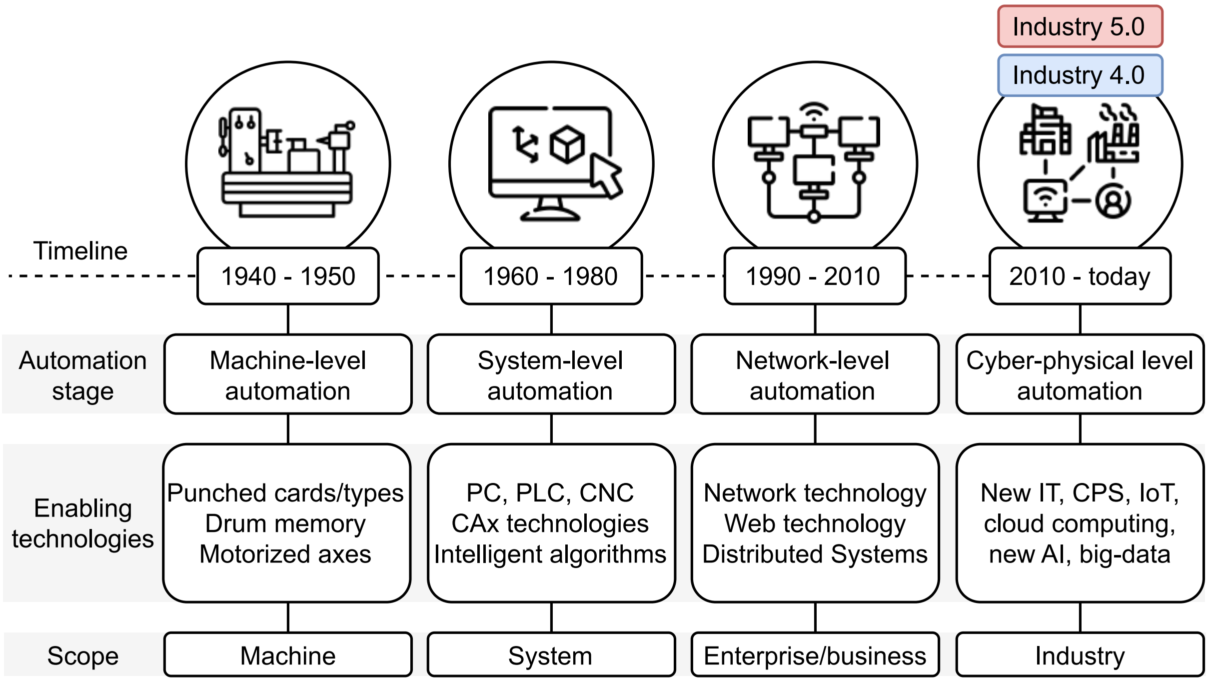


Figure 1.1: Stages of manufacturing automation throughout the digital evolution. Font: Author

for the birth of Computer-Aided technologies (CAx) and Computer Numerical Control (CNC). Machine tools underwent a transformative change, allowing them to interpret numerical command lines in the G-code format (released in 1979 as RS-274 [8], later formalized as ISO 6983 in 1982 [9]). This breakthrough allowed complex design and manufacturing operations to be executed with improved efficiency and effectiveness [10].

The third stage, network-level automation (1990-2010), brought a revolutionary transformation to the manufacturing industry by integrating processes and network technology, facilitated by the expansion of the Internet. This era marked the introduction of distributed [11], collaborative [12], and flexible [13] manufacturing approaches. Furthermore, through the implementation of intelligent manufacturing techniques, operations and decision-making were optimized, propelling the industry toward a new era of intelligent manufacturing [14]. Moreover, advanced manufacturing systems equipped with network connectivity facilitated real-time monitoring and remote operation via the Internet [15]. This stage of digital transformation empowered companies to harness the potential of e-Commerce and web-based manufacturing services, opening up new avenues for value creation.

Today, we are witnessing the fourth stage of manufacturing automation, operating at the cyber-physical level. This highly impactful degree of digitalization is triggering an authentic renaissance in the realm of manufacturing, manifesting in the form of the fourth industrial revolution, the so-called Industry 4.0. Industry 4.0 aims to transform traditional industrial production systems into a new generation of Smart Factories for the future that are characterized by increased intelligence, flexibility, reconfigurability, and sustainability [16]. To achieve this, Industry 4.0 emphasizes the integration of advanced manufacturing systems and new generation information technologies (new IT) such as Cyber-Physical Systems (CPS), Internet of Things (IoT), Cloud Computing (CC), Artificial Intelligence (AI), and Big-Data Analytics (BDA) [17].

Industry 4.0, initially introduced as a German initiative (I4.0 program) to secure the future of the national industry [18], has now become a global movement with governments worldwide leveraging its potential through similar initiatives, e.g., "Industrial Internet of Things (IIoT)" in the United States, 2012; "Industry 4.0" in the European Union, 2014; "Japan Industry 4.0" in Japan, 2014; "Made in China 2025" in China, 2015; and, "*Agenda brasileira para a Indústria 4.0*" in Brazil, 2017 [19]. These initiatives share a common goal: to achieve more efficient and competitive industrial production by implementing highly intelligent and autonomous manufacturing systems. That is, the forthcoming Smart Manufacturing (SM) [20]. Currently, on the ten-year anniversary of Industry 4.0, the European Commission unveiled Industry 5.0, a paradigm shift from technology-driven Industry 4.0 to a more value-driven approach [21].

Smart manufacturing is the driving force behind Industry 4.0. It represents the next generation of manufacturing systems that describe the production of tomorrow [22]. According to the National Institute of Standards and Technology (NIST), smart manufacturing systems are characterized as "fully integrated collaborative manufacturing systems that respond in real time to meet changing demands and conditions in the factory, in the supply network and customer needs" [23]. This transformative approach to manufacturing involves two key paradigm shifts: transition from knowledge-based intelligent manufacturing to data-driven and knowledge-enabled smart manufacturing [24], and shifting from ERP (Enterprise Resource Planning [25])/MES (Manufacturing Execution Systems [26])/multi-agent [27] based production systems to CPS-based production systems (CPPS).

Through the implementation of smart manufacturing, embodied by CPPS, Industry 4.0 holds the promise of enhanced productivity, increased cost-effectiveness, and the pursuit of sustainable growth. One of its primary commitments lies in achieving on-demand product individualization, enabling the efficient production of single, tailor-made product units (also referred to as "batch size one") to meet the unique demands of each customer [28]. For this purpose, it underscores the service-oriented arrangement of manufacturing resources and operations in the cloud [29]. In addition, it pledges to significantly reduce time-to-market, expediting the journey from product conception to final delivery [30]. Energy efficiency is also a central focus, offering the potential for decreased energy consumption through advanced automation and data-driven processes, resulting in both environmental benefits and substantial cost savings [31]. Moreover, in an increasingly unpredictable world, Industry 4.0 equips companies with the agility and flexibility to respond promptly to supply chain disruptions like those triggered by the COVID-19 pandemic [32], ensuring continuity in production, strengthening resilience and minimizing economic shocks.

On the other hand, CPS is a broad concept within Industry 4.0 that signifies the integration of computation and physical processes, utilizing embedded computers and networks to monitor and control these processes in a mutually influencing loop [33]. Meanwhile, CPPS comprises the application of CPS principles in the domain of production management to achieve smart manufacturing in Industry 4.0 environments. These systems include smart machines, warehousing systems and manufacturing facilities, tightly integrated end-to-end through information and communication technologies [18]. They act as complex networks of interconnected, autonomous and cooperative elements that operate at all levels of production, improving real-time decision making, adaptability, and responsiveness [34]. According to [35], potential benefits of CPPS include optimized production processes, enhanced product customization, resource-efficient production, and human-centered manufacturing.

Within CPPS, the continuous and dynamic interaction between physical and virtual spaces is characterized by synchronized bidirectional real-time data flow [36]. Real entities in the physical space, encompassing manufacturing assets like machine tools, robots, 3D printers, products, or an entire factory, are equipped with sensors that transmit data to their digital counterparts in the virtual space. Simultaneously, in the virtual space, these digital replicas/copies, known as Digital Twins [37], possess the capability for comprehensive data utilization, including storage, processing, analysis, and simulation, which aims to facilitate the autonomous learning and optimized decision-making directly impacting physical manufacturing processes.

At the forefront of the digitalization wave, Digital Twins (DTw) are recognized as the technological core within every CPPS and are deemed as a key technology for Industry 4.0 [38]. This breakthrough technological advancement is now being championed to disrupt the status quo of the manufacturing industry. According to a recent report from MarketsandMarkets, the global market of DTw is poised for substantial growth, forecasted to surge from USD 10.1 billion in 2023 to USD 110.1 billion by 2028 [39]. As expected, DTw technology has garnered strong interest from both the academic community and industry practitioners alike. Some scholars have highlighted the significant growth in research work concerning the development of DTw [37, 40]. Certainly, prominent technological players have also spearheaded the development of DTw products/services. For instance, Dassault Systèmes offers "3DEXPERIENCE Twin" [41], Siemens provides "Teamcenter X" [42], IBM presents "Watson IoT Platform" [43], and Microsoft has introduced "Azure Digital Twins" [44].

DTw technology finds applications in a myriad of industries, including aerospace [45], healthcare [46], agriculture [47], smart cities [48], and, of course, manufacturing [49]. Manufacturing stands as a promising arena for the successful application of DTw, yielding concrete benefits in optimized design, advanced simulation, real-time process monitoring, equipment provisioning and maintenance, adaptive quality control, and autonomous decision-making. As such, DTw play a crucial role in the realization of SM. Despite its remarkable progress in the manufacturing domain, there is a significant gap in the actual development and deployment of digital ecosystems fueled by DTw solutions robustly supported by integrated data across the various stages of Digital

Thread (DTh). Particularly in the Additive Manufacturing (AM) processes, seamless data integration and management from design to post-processing stages is crucial for process efficiency and product quality. Addressing this gap requires industry stakeholders to prioritize standardized digital ecosystems fueled by DTh and DTw technologies. Through concerted efforts in research, development, and implementation, the AM industry can bridge this gap and pave the way for transformative advancements aligned with the principles of Industry 4.0. This elicits the definition of the research problem and the motivation for this thesis work.

1.2 Research problem: definition and motivation

In the context of massive digitization, the visionary concepts of DTw and DTh emerge, with data serving as their lifeblood flowing through the veins of cutting-edge information systems. Intricately related, these concepts share a reliance on data-driven technologies that form the backbone of their functionalities.

On the one hand, DTh represents the seamless and traceable flow of data that moves between information systems throughout various stages in a product's lifecycle, spanning from its inception to eventual disposal. It can be seen as the digital counterpart of the traditional Product Lifecycle Management (PLM) process. On the other hand, DTw act as virtual replicas of specific physical entities within the PLM process or from one or more designated phases along the DTh, providing real-time insights and simulations based on their current or historical data. Importantly, it is worth noting that neither concept emerges to replace the other; instead, they are designed to complement each other, each serving a distinct purpose, role, and contribution within the broader digitalization landscape. As such, both are crucial for companies to extract maximum value from the extensive data generated across the product development lifecycle, offering intelligent and cohesive approaches to integrate data, knowledge, and processes.

Pioneering efforts in DTw and DTh made by the defense and aerospace industries have explored their potential benefits, now extending beyond their sectors. Boeing and Airbus, for instance, use these technologies to streamline aircraft design and assembly, enabling comprehensive assessment and predictive analysis of component performance throughout their lifecycle [50, 51]. By integrating real-time data collection, advanced analytics, and machine learning, they create dynamic virtual replicas of physical systems, enabling predictive maintenance, streamlined manufacturing, and enhanced operational reliability. These innovations allow comprehensive performance simulations and informed decision-making, addressing the challenges of increasing airspace complexity and demand for highly reliable aircraft. Through these efforts, both companies drive the digital transformation of aerospace engineering, setting new benchmarks for efficiency and safety in aviation.

Lockheed Martin's maturity model for DTh and DTw visualization ensures alignment of capabilities, technologies, and investments for authentic interoperability along their warfighters [52]. By treating data as a strategic asset and utilizing real-time insights across the product lifecycle, this model promotes standardization and interoperability, enabling predictive decision-making and transparency. It supports complex mission demands by aligning industry efforts toward Joint All-Domain Operations, ensuring their warfighters benefit from data-driven collaboration and accelerated progress across aerospace and defense programs.

NASA employs DTw for future vehicle generations, merging high-fidelity simulations and onboard data for safety and reliability [45]. By combining real-time sensor updates with predictive modeling, NASA uses DTw to continuously forecast system health, evaluate remaining useful life, and adapt mission parameters, ultimately redefining certification, fleet management, and sustainment practices for lighter, more resilient vehicles operating in demanding environments. This approach ensures unprecedented safety and reliability by mirroring the life of physical counterparts under extreme conditions.

Similarly, General Electric uses a DTw for the Boeing 777's GE90 engine to manage aircraft engine blades, tackling challenges such as "spallation" caused by erosion in sandy conditions [53]. By combining real-time data with predictive modeling, GE's DTw not only enhances situational awareness but also streamlines maintenance planning, reduces downtime, and ensures safety. This approach allows engineers to visualize asset behavior dynamically, enabling proactive maintenance and improved engine efficiency under demanding conditions. STEP Tools Inc has demonstrated the practical application of DTh and DTw in manufacturing, showcasing real-time updates of machining twin models, improved efficiency through online and off-line monitoring, and cost reduction through cloud services and shop floor control [54].

Notably, in a scenario that is reminiscent of fiction but is a true endeavor, Singapore is creating a DTw for the whole country [55], to address challenges like land scarcity, flooding, and infrastructure management in one of the world's most densely populated nations. Using advanced technologies such as laser-scanning aircraft, vehicle-mounted sensors, and software from Bentley Systems, the project integrates detailed aerial and street-level data into a 3D interactive model. This DTw supports urban planning, flood risk analysis, utility management, emergency preparedness, and network optimization, enabling real-time insights and simulations to improve safety, efficiency, and resource allocation across government, private, and public sectors.

While major industries have made strides, the development of DTw and DTh technologies is still incipient, with much ground to cover. Their complete implementation remains a complex challenge, particularly for small and medium enterprises with limited resources and technological development. The innovative nature of these technologies, along with the confusion surrounding their definitions, connotations, and the technologies to be employed, also creates barriers to widespread industry adoption. In addition, substantial challenges persist in achieving seamless integration and interoperability across different operational levels: between stages of the DTh, between DTw and other entities, and also between DTh and DTw. These challenges are primarily attributed to the heterogeneity of: data itself, file formats for data exchange, communication protocols, and existing implementation frameworks.

According to a study [56], companies are missing up to 65% of the potential value of their DTw by relying on the development of standalone DTw for a single purpose. To unlock this value, a shift towards comprehensive DTh is crucial, serving as the foundation for sustained growth and success of DTw. In other words, there should be systematic integration and interoperability between DTh and DTw. The conventional "throw it over the wall" approach to department handovers involves disjointed processes, from 3D model creation to production, leading to data silos and inefficiencies [57]. In contrast, the synergy between DTh and DTw can eliminate these barriers, fostering seamless collaboration, linking real-time design changes, and optimizing the entire product lifecycle. However, it is important to note the limited research that specifically addresses the integration of DTh and DTw, as reflected in Table 1.1.

Kraft [58] and Zweber et al. [59] have investigated the integration of DTh/DTw, particularly within the U.S. defense air force context. West and Blackburn [60] highlight the importance of feasibility studies for the implementation of DTh and DTw in defense. Zhang et al. [61] proposed a DTh/DTw framework to support aircraft assembly operations. Bachelor et al. [62] utilized DTh and DTw for Model-based Design (MBD) data management in aeronautic applications, while Jagush et al. [63] explored DTh as a prerequisite for DTw in shipbuilding applications. Pang et al. [64] developed a DTh/DTw framework for data management with applications in the shipyard industry. Jiang et al. [65] proposed combining DTh and DTw in a framework for efficient product-part design. Additional studies [66, 67, 68, 69] have concentrated on reviewing DTh and DTw concepts and platform propositions within the Industry 4.0 context.

Table 1.1: Research works focused on the integration of DTh and DTw.

Reference	Purpose	Application domain
[58, 59, 60]	Review of DTh and DTw integration with focus on defense industry	Defense industry
[61]	DTh/DTw framework to support aircraft assembly operations	Aerospace/aircraft industry
[62, 63]	Model-based DTh and DTw for managing model-based design (MBD); DTh as prerequisite for building DTw in shipbuilding	Aeronautic/shipbuilding industry
[64]	Framework that combines the DTh and DTw for data management	Shipyard industry
[65]	Product DTw supported by DTh framework	Product-part design
[66, 67, 68, 69]	Review of DTh and DTw concepts; DTh and DTw Industry 4.0 platform propositions	Generic Industry 4.0 applications

The mentioned studies highlight the benefits of integrating DTh and DTw, while recognizing the ongoing efforts needed to overcome the challenges in their implementation. However, these investigations have predominantly focused on conceptualizing a broad integration of DTh and DTw within the product development cycle within a specific industrial domain. Turning our attention to AM processes, it is noteworthy that most existing DTw implementations are currently developed as standalone applications, each tailored for specific tasks such as in-process monitoring [70], mechanistic models for predictive analysis [71], and process parameter optimization [72]. A comprehensive and systematic approach for developing a digital ecosystem that seamlessly merges DTw technology with the DTh in AM processes, fostering the integration, interoperability, sharing, and management of data collected from the entire AM part[1] lifecycle, is yet to be fully realized.

As for AM, its DTh consists of a series of stages that include part design or scanning, geometry tessellation, part model creation, preparation for build, machine code generation, manufacturing, post-processing, and part inspection and validation [73]. Each stage generates many heterogeneous data that can influence the quality of the manufactured part. However, data management, sharing, integration, and interoperability across the DTh continue to face cumbersome limitations that can seriously hinder the widespread adoption of AM in Industry 4.0 smart manufacturing environments.

Traditionally, the AM DTh encounters multifaceted challenges that impede seamless data integration, sharing, and interoperability across its various stages, including design, planning, manufacturing, inspection, and post-processing. These challenges contribute to inefficiencies and bottlenecks in the AM process. Information isolation and loss hinder a holistic understanding of the manufacturing context, leading to suboptimal decision making. Redundant information and diverse file formats increase the complexity of data management and sharing, creating barriers to effective collaboration. The unidirectional data flow restricts the establishment of feedback loops essential for real-time adjustments and optimizations. Moreover, the limited intelligence of machine CNC controllers limits adaptive and intelligent[2] control over the manufacturing process [74].

Similarly, DTw in the context of AM faces its own set of limitations. Current implementations often operate in "silos", focusing on modeling specific lifecycle stages of physical elements. This siloed approach makes it challenging to analyze or compare features across diverse lifecycle stages, limiting the holistic insights that a comprehensive DTw could provide. Furthermore, collaboration methods between DTw manufacturing units and the incorporation of diverse data streams from different lifecycle stages remain underexplored. This lack of breakthroughs in col-

[1]In this text, the terms "part," "piece," and "component" are interchangeable, signifying a physical object created through manufacturing processes

[2]In this context, "intelligence" refers to the ability of CNC controllers to go beyond executing numerical commands and instead analyze high-level information to develop a form of self-awareness of their operations. This enables them to perform adaptive adjustments to the manufacturing process and make informed decisions in real time.

laboration methods and quality status monitoring hampers the full potential of DTw in contributing to the optimization of AM processes.

In essence, the limitations of DTh and DTw in AM underscore the critical need for comprehensive solutions that address data integration, interoperability, collaboration, and the efficient utilization of heterogeneous data. Overcoming these challenges is essential to unlock the full potential of AM in the 4.0 landscape of Smart Manufacturing and Industry 4.0.

1.2.1 Research question

In light of the context mentioned above, the following two key research questions arise:

- What systematic approaches can tackle the challenges of integrating, exchanging, and managing data when implementing Digital Twins and the Digital Thread in AM?
- Which standards and technologies provide a robust foundation for establishing a cohesive digital ecosystem in AM?
- What are the main challenges in implementing these technologies, and how can these obstacles be effectively mitigated?

1.2.2 Hypothesis to test

We hypothesize that a standardization-driven approach to establish a new digital ecosystem for additive manufacturing, powered by DTw and the DTh, can propel AM to the next generation of advanced manufacturing systems, aligning with the demands of Industry 4.0. Standard-based technologies are expected to play a pivotal role in propelling current AM towards greater data integration and interoperability, extensive collaboration, robust connectivity and enhanced intelligence in harmony with the requisites of Industry 4.0.

1.3 Objectives

The primary objective of this thesis is to propose a systematic methodology for developing a digital ecosystem for AM, driven by standards-based DTh and DTw technologies, to address challenges of data integration, interoperability, and collaboration.

1.3.1 Specific objectives

To fulfill the primary objective of this thesis proposal, the subsequent specific objectives are proposed as follows:

- Investigate and analyze existing standards, data exchange formats, and communication protocols to establish a foundational framework to construct a standards-driven digital ecosystem for additive manufacturing.
- Design and propose a novel digital ecosystem architecture for additive manufacturing, driven by standards-based DTh and DTw technologies, to enable seamless integration, interoperability, and data management.
- Develop and evaluate implementation scenarios to validate the feasibility and effectiveness of the proposed digital ecosystem in real-world additive manufacturing environments.

1.4 Contributions

Scientific and technological contributions:

- **Proposed digital ecosystem (Chapter 6)**
  - Developed a standards-based digital ecosystem integrating DTh and DTw technologies to enable more interoperable, collaborative and intelligent manufacturing systems.
  - Proposed a structured approach for integrating multiple DTh within the proposed digital ecosystem.
- **STEP-NC industrial robotic machining (Chapter 7)**
  - Demonstrated the feasibility of using STEP-NC to program and simulate robotic machining operations, highlighting the adaptability of STEP-NC in robotic contexts.
  - Developed a software adapter that converts APT machining commands into STEP-NC programs. Available on repository in [75].
- **Integrating STEP-NC and MTConnect in AM (Chapter 7)**
  - Method to adapt the machining-oriented STEP-NC model for FDM processes.
  - Software to convert XML AM layer data to STEP-NC program. Available on the repository in [76].

- 3D kinematic model of the RepRap Prusa 3D printer for STEP-NC Machine. Available on teh repository in [77].
- MTConnect adapter for real-time monitoring of RepRap 3D printers, enabling the tracking of print progress, bed and hotend temperatures, X, Y, and Z axis positions, as well as the printing speed.
- Adapter code included into the Sprinter firmware. Available on the repository in [78].

- **STEP-NC simulation for LMD (Chapter 7)**
  - Simulated toolpaths for robotic LMD processes, showcasing STEP-NC capability in metal AM operations.
  - 3D kinematic model of the KUKA KR 70 robot for STEP-NC Machine. Available on teh repository in [79].

- **EXPRESS entities for FDM and LMD (Chapter 7)**
  - Created new EXPRESS-based STEP-NC entities tailored to FDM and LMD processes, addressing process-specific parameters such as nozzle diameter, hotend temperature, extrusion speed, laser power, and wire feed rate. This provides a call to action for ISO TC184/SC4 to consider these models for validation and inclusion in the STEP-NC standard.

- **New STEP-NC library (Chapter 7)**
  - Created an open-source, extensible TypeScript library to handle STEP-NC models, supporting serialization to Part 21 and JSON formats and enabling web-based applications.
  - Designed the library for extensibility, allowing the inclusion of new entities and schemas to adapt to evolving manufacturing requirements.
  - Addressed the lack of accessible tools for STEP-NC, making the library openly available on npm and promoting collaboration and adoption within the research and industrial communities. Available on npm in [80].
  - Pioneered novel implementations of STEP-NC for AM processes, contributing foundational knowledge and tools for its evolution in research and industry.

Academic contributions:

Peer-Reviewed Publications: The findings and advancements achieved through this research have resulted in more than seven publications in international journals, including:

- (Under review) **The International Journal of Advanced Manufacturing Technology**: STEP-NC in Additive Manufacturing: A Comprehensive Review, Architecture and Data Model Proposal.
- **Procedia Manufacturing**: A STEP-NC implementation approach for additive manufacturing.
- **Brazilian Journal of Development**: Modelo de información para manufactura aditiva basado en STEP-NC.
- **IFAC Proceedings Volumes**: Developing a MTConnect Framework for RepRap Additive Manufacturing Machines.
- **IEEE Access**: STEP-NC Architectures for Industrial Robotic Machining: Review, Implementation and Validation.
- **The International Journal of Advanced Manufacturing Technology**: Expert system to implement STEP-NC data interface model on CNC machine.
- **IEEE Latin America Transactions**: Digital Twin Implementation for Machining Center Based on ISO 23247 Standard.
- **IFAC Proceedings Volumes**: A Closed-Loop Inspection Architecture for Additive Manufacturing Based on STEP Standard.
- **International Journal on Interactive Design and Manufacturing (IJIDeM)**: New system architecture and algorithm design for indirect STEP-NC implementation.

The details of these articles are presented in the Appendix A.

1.5 Document organization

Chapter 2 presents an exploration of pivotal technological concepts, traversing the realms of Industry 4.0, Reference Architecture Models, Smart Manufacturing, Cyber-Physical Systems, Cyber-Physical Production Systems, Additive Manufacturing, and Communication Protocols (MTConnect, OPC-UA, MQTT). This foundational chapter lays the groundwork for understanding the technological landscape surrounding the core themes of the document.

Chapter 3 delves into PLM and the DTh, unraveling their foundational concepts and roles in fostering connectivity and traceability in the manufacturing ecosystem. The exploration extends to the unique advantages of the DTh in the context of AM processes, accompanied by a scrutiny of potential drawbacks that demand innovative solutions.

Chapter 4 focus on the concept of DTw, offering an in-depth exploration of their definitions, distinctive characteristics, reference architectures in the manufacturing domain, and specific applications in AM processes. This section illuminates how DTw are fundamentally transforming modern manufacturing, creating innovative connections between the physical and digital realms.

Chapter 5 provides an in-depth literature review of the current state of STEP-NC applications in AM. It highlights the challenges, gaps, and opportunities for advancing STEP-NC to meet the unique needs of AM technologies.

Chapter 6 presents a comprehensive proposal for a digital ecosystem framework tailoredThis chapter presents the conceptual framework for a robust digital ecosystem leveraging STEP and STEP-NC as central standards. It integrates open standards such as ISO 23247, QIF, MTConnect, OPC-UA, and MQTT to enhance data interoperability and contextual management throughout the manufacturing lifecycle.

Chapter 7 describes the practical implementation scenarios carried out to validate the proposed approaches, including robotic machining, FDM and LMD processes using STEP-NC, and integration with cyber-physical systems using MTConnect. These scenarios demonstrate the applicability and limitations of current STEP-NC implementations while identifying opportunities for further development.

Chapter 8 presents the conclusions derived from the research conducted within the scope of this thesis, highlighting the main contributions of the work, and providing recommendations for future research.

Chapter 2

Theoretical background

2.1 Industry 4.0

Manufacturing is the transformative process of turning raw materials into valuable end products. From everyday items like clothing to the vehicles and airplanes moving our world, have been manufactured through a process involving materials, machinery, resources, energy, and labor. Changes in the way products are manufactured and consumed have led to shifts in industrialization, giving rise to authentic industrial revolutions. These industrial revolutions have fundamentally altered production methods, introducing innovations and reshaping industries throughout history, with a profound impact on the global economy and human development.

The ongoing fourth industrial revolution, known as Industry 4.0, follows the mechanization (Industry 1.0), electrification (Industry 2.0), and information (Industry 3.0) revolutions [81]. Originating in the late 18th century, the first revolution (Industry 1.0) introduced steam engines and mechanized looms, while the second one (Industry 2.0), in the early 20th century, embraced electricity and mass production, notably in the automotive sector. The third revolution (Industry 3.0), starting in the 1970s, saw the ascendancy of semiconductor materials, leading to the emergence of microelectronics, personal computers, and programmable logic controllers, paving the way for automation and advanced manufacturing systems. Figure 2.1 illustrates the progression through the four stages of the industrial revolution.

Industry 4.0, also named as Industrie 4.0 in German, was initiated by the German government in 2011 as part of the High-Tech Strategy 2020 action plan, with a substantial annual financial commitment [18]. As highlighted in the contextualization previously, this movement relies on the seamless integration of cutting-edge technologies, such as the CPS, IoT, cloud computing, artificial intelligence, and big data analytics, into industrial manufacturing processes. By cultivating a connected ecosystem of smart devices and systems, Industry 4.0 envisions a highly efficient and flexible production environment. Even today, it remains a trending topic within the academic research community. Several earlier studies have investigated the concept, related technologies,

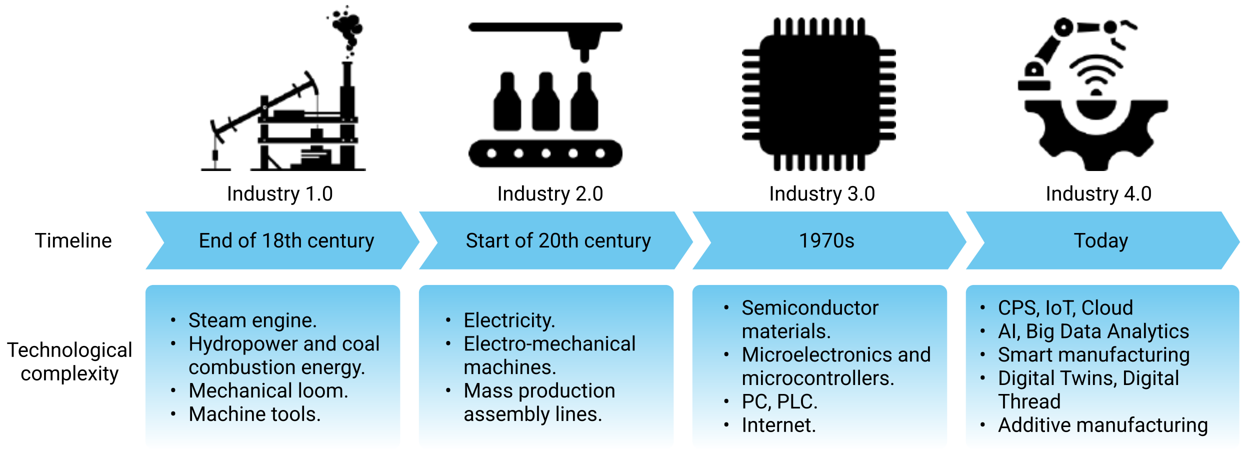


Figure 2.1: The four stages of the Industrial Revolution. Adapted from [18]

and future trends of Industry 4.0 [82, 83]. Some works have introduced maturity models for its integration into enterprises [84, 85], while other have examined frameworks and scenarios for its implementation in the form of smart manufacturing systems [20].

Hermann et al. [86] emphasize the significance of technological concepts like IoT, CPS, Smart Factories, and the Internet of Services (IoS) in Industry 4.0 research, categorizing them as fundamental components. Further expansion on these concepts will be provided later in this text. Additionally, they have advocate the establishment of design principles for successful Industry 4.0 pilot projects. Table 2.1 illustrates the six design principles they proposed, associated with the components of Industry 4.0.

Table 2.1: Design principles associated to each Industry 4.0 component [86].

	CPS	**IoT**	**IoS**	**Smart Factory**
Interoperability	X	X	X	X
Virtualization	X			X
Decentralization	X			X
Real-Time Capability				X
Service Orientation			X	
Modularity			X	

In Industry 4.0, **interoperability** serves as a linchpin, connecting CPS and humans via the IoT and the IoS. The establishment of standards becomes pivotal for effective communication across diverse CPS from various manufacturers [86]. Meanwhile, **virtualization** introduces the capability for CPS to monitor physical processes, creating a virtual counterpart through the integration of sensor data with plant and simulation models. This virtual representation enables real-time condition monitoring and alerts for timely response to failures [86].

Decentralization in Industry 4.0 empowers CPS with embedded computing capabilities to make autonomous decisions, diminishing the reliance on centralized control. In practical terms, this means RFID tags communicate necessary working steps to machines, eliminating the need for centralized planning within smart factories [86]. Similarly, **real-time capability** ensures swift data collection and analysis, allowing continuous monitoring of the plant's status. This real-time responsiveness enables the plant to react promptly to machine failures, rerouting products to alternative machines [86].

Service orientation enables the availability and utilization of services from companies, CPS, and humans, extending across organizational boundaries through the IoS. Companies adopt a service-oriented architecture, encapsulating CPS functionalities as web services, allowing customizable process operations based on RFID-tagged customer requirements. Lastly, **Modularity**, a hallmark of Industry 4.0, facilitates adaptability to changing needs by easily replacing or expanding individual modules. Companies can embrace this by incorporating a plug-and-play approach, seamlessly adding new modules and ensuring automated identification and utilization through standardized software and hardware interfaces.

Nevertheless, for Industry 4.0 to fully deliver its benefits, comprehensive standardization is crucial. From the system landscape to communication structures, a clear and agreed-upon framework is essential. In this sense, reference models and architecture frameworks stand out as indispensable tools, providing systematic and standardized approaches to interconnect technologies and industrial systems. These frameworks not only simplify intricate tasks such as data acquisition and processing but also establish a common language and structure with technologies, procedures, standards, and best practices that can be used in Industry 4.0 applications.

In the following, attention is now directed to the description of a highly relevant reference architecture model for Industry 4.0, widely accepted and applied by manufacturing companies.

2.1.1 Reference Architecture Model for Industry 4.0 (RAMI 4.0)

The "Platform Industrie 4.0" working group has introduced the Reference Architectural Model for Industry 4.0, known as RAMI 4.0 [87], established through consensus among associations like BITKOM, VDMA, ZVEI, Measurement and Automatic Control (GMA), German Commission for Electrical Engineering (DKE), and others German industrial enterprises. The RAMI 4.0, depicted in Figure 2.2, stands as a pivotal framework offering comprehensive guidelines for the systematic implementation of Industry 4.0 within industrial production systems. This sophisticated model is ingeniously structured along a three-dimensional coordinate system, each axis contributing to the holistic understanding and integration of cutting-edge technologies.

Within RAMI 4.0, the axis dedicated to the product lifecycle and value stream draws inspiration from the evolving IEC 62890 standard, introducing a crucial distinction between "types" and "instances." During the product design phases, including development, simulation, and prototyping, assets are categorized as "types," transforming into "instances" once actual production

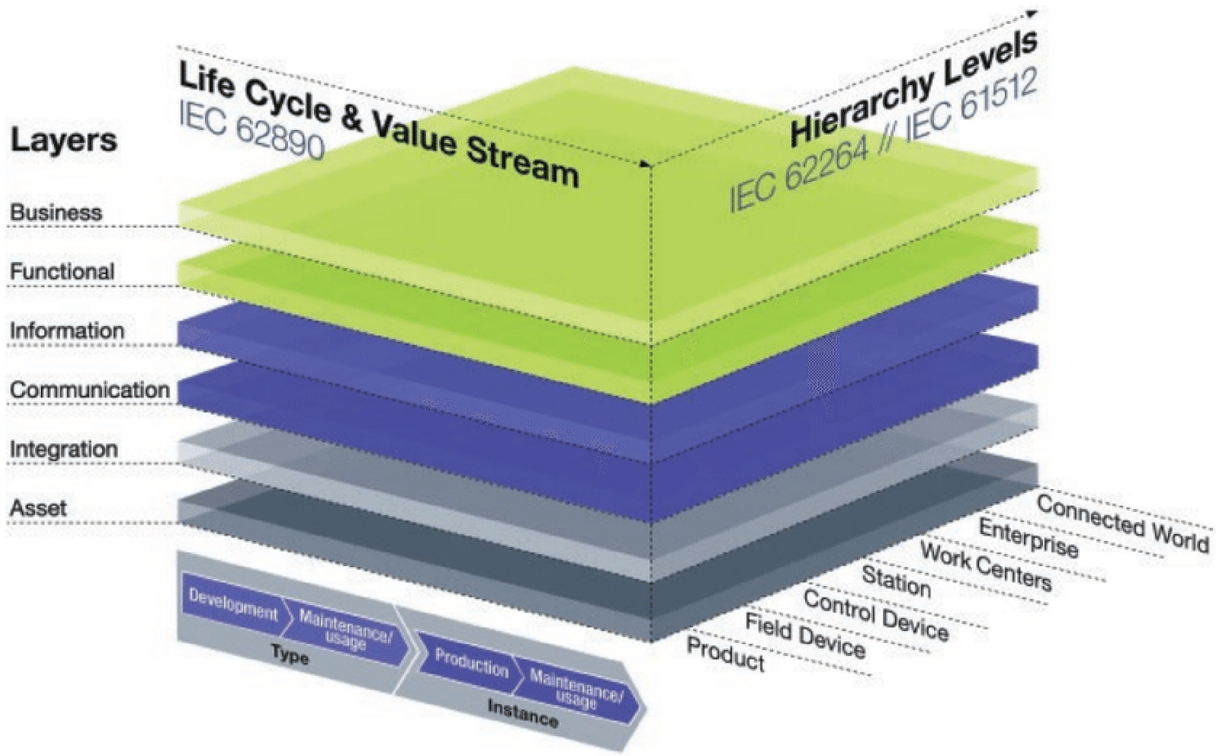


Figure 2.2: Reference architecture model for Industry 4.0 (RAMI4.0) [87]

commences, highlighting the dynamic evolution within the manufacturing process.

The vertical axis serves as a visual representation of interoperability layers, synonymous with architectural layers, offering insights into the IT structure of Industry 4.0. Comprising six layers—business, functional, information, communication, integration, and asset—this axis comprehensively covers aspects ranging from business processes to communication standards, encompassing both physical components and human elements integral to the operational process.

The hierarchy levels, akin to the automation pyramid modeled after the IEC 62264 standard, delineate diverse participants within the network. This hierarchy spans products, field devices, control devices, stations, work centers, the enterprise, and extends upward to the interconnected world. It is essential to emphasize that, within RAMI 4.0 and Industry 4.0 at large, products seamlessly integrate into the network, facilitating communication on par with other participants.

Moreover, RAMI 4.0 incorporates an asset administration shell that acts as the digital core, orchestrating the creation of DTw throughout the digitized asset lifecycle; that is, the DTh [88, 89]. This dynamic representation captures and integrates real-time insights, optimizing the asset's journey from conception to realization. RAMI 4.0 is a way to integrate DTh and DTw, advancing Smart Manufacturing systems within Industry 4.0, gaining increasing acceptance and significance not only in academia but also in industry [90, 91].

As the concept of Industry 4.0 continues to evolve, various initiatives, including "IIoT" in the

United States, "Industry 4.0" in the European Union, "Japan Industry 4.0" in Japan, "Made in China 2025" in China, and the "Agenda brasileira para a Indústria 4.0" in Brazil, have emerged to harness its potential. The Brazilian initiative, for example, underscores the nation's commitment to this global paradigm shift, aligning itself with the goal of fostering highly intelligent and autonomous manufacturing systems within Brazil's industrial landscape [19]. This commitment resonates with the shared notion among all these movements to transition towards smart manufacturing, marking a collective effort to embrace and advance the principles of Industry 4.0.

2.2 Smart Manufacturing (SM)

According to the historical perspective presented by Wang et al. [24], the genesis of SM can be traced back to the late 1980s. In 1986, Schaffer [92] and, in 1987, Krakauer [93] were the first to coin the term "Smart Manufacturing", exploring the application of expert system AI for enhancing productivity and profitability in manufacturing operations. However, the term lay dormant for three decades until the advent of Industry 4.0. Now, it is regarded as the new generation of manufacturing excellence centered around cutting-edge technologies such as CPS, IoT, Cloud Computing, new AI, and Big Data Analytics, heralding a new era of industrial innovation. This recognition heralds a new era of industrial innovation, showcasing the transformative impact of these technologies on manufacturing processes and operations.

Concerning the conceptual definitions of smart manufacturing, NIST and the Smart Manufacturing Leadership Coalition (SMLC) have introduced the most widely accepted definitions. NIST defines SM as "fully-integrated, collaborative manufacturing systems that respond in real time to meet changing demands and conditions in the factory, in the supply network, and customer needs" [23]. Meanwhile, according to the SMLC, it is characterized as the "dramatically intensified application of manufacturing intelligence throughout the manufacturing and supply chain enterprise" [94]. In this sense, Wang et al. [24] have compiled three definitions from the literature, covering perspectives in engineering, networking, and decision-making.

- From an engineering perspective, SM deploys advanced technologies for rapid, stable production of new products, personalized responsiveness, and real-time supply chain optimization.
- On the other hand, from a networking perspective, it enables data capture at all manufacturing levels, leading to increased productivity and decreased errors and waste over time by the application of CPS, IoT, and IIoT technologies.
- Lastly, in a decision-making perspective, SM leverages domain data accessibility and big data analytics capabilities to predict, optimize, and maintain production processes, enhancing overall productivity.

Wang et al. [24] have conducted a thorough examination of the distinctions and similarities between smart manufacturing and intelligent manufacturing, focusing on their origins, definitions, capabilities, principles, and related technologies. Their analysis reveals that SM is more frequently associated with concepts such as Industry 4.0, data-driven approaches, and big data, whereas intelligent manufacturing is more closely linked to concepts like AI algorithms, optimization, agents, and architecture. Despite these disparities, they emphasize that both are crucial paradigms shaping the new industrial landscape of Industry 4.0.

SM's progress stimulated researchers, consortia, and discussion groups to develop architectures, frameworks, roadmaps, and platforms, reflecting a dynamic collaboration among various stakeholders. The SMLC, which is formed by a coalition of companies, universities, manufacturing consortia, and consultants, has established a general collaborative platform for SM [94] that focuses on significant objectives: reducing costs for manufacturing-oriented modeling and simulation, lowering IT infrastructure expenses, providing access to SM applications, and creating an enterprise digital layer for applied manufacturing intelligence. Furthermore, the platform facilitates test bed demonstrations and encourages the dynamic involvement of enterprises across the spectrum from small to large.

One key outcome of these efforts is the creation of an industry-driven Virtual Smart Manufacturing Demonstration Facility (V-MDF) by seamlessly integrating pre-competitive and competitive web-based resource spaces [94]. The V-MDF offers workflow tools for assembling real-time data, supporting application models and metric calculations into active performance management dashboards. It supports workflow-compatible applications for validating data, projecting performance, and assessing scenario-based decision risks. The V-MDF enables rapid evaluation of models and toolkits, standardizes models for consistent use and results, facilitates software development, and engages entrepreneurs in developing new software modules, ultimately contributing to faster, easier, and more cost-effective advancements in Smart Manufacturing.

Consolidating precise and specific architectures from the overarching principles of SM is imperative, as emphasized by Kwziak [22]. Zheng et al. [20] have proposed a systematic framework for smart manufacturing systems in Industry 4.0 application scenarios. Illustrated in Figure 2.3, their framework facilitates the transformation of activities/operations occurring throughout the product lifecycle into intelligent processes, encompassing smart design, smart machining, smart monitoring, smart control, and smart scheduling. The horizontal axis outlines these manufacturing activities, while the vertical axis covers a data dimension, spanning sensor and actuator deployment, data collection, big data analysis, and data-driven decision-making. They assert that their framework guides academics and industry professionals in implementing SM across varied applications, emphasizing the need for future work in data collection, visualization, and decision-making.

Tao et al. [95] have introduced a conceptual framework for data-driven smart manufacturing, leveraging big data strategy to analyze and manage the increasingly vast volumes of data gener-

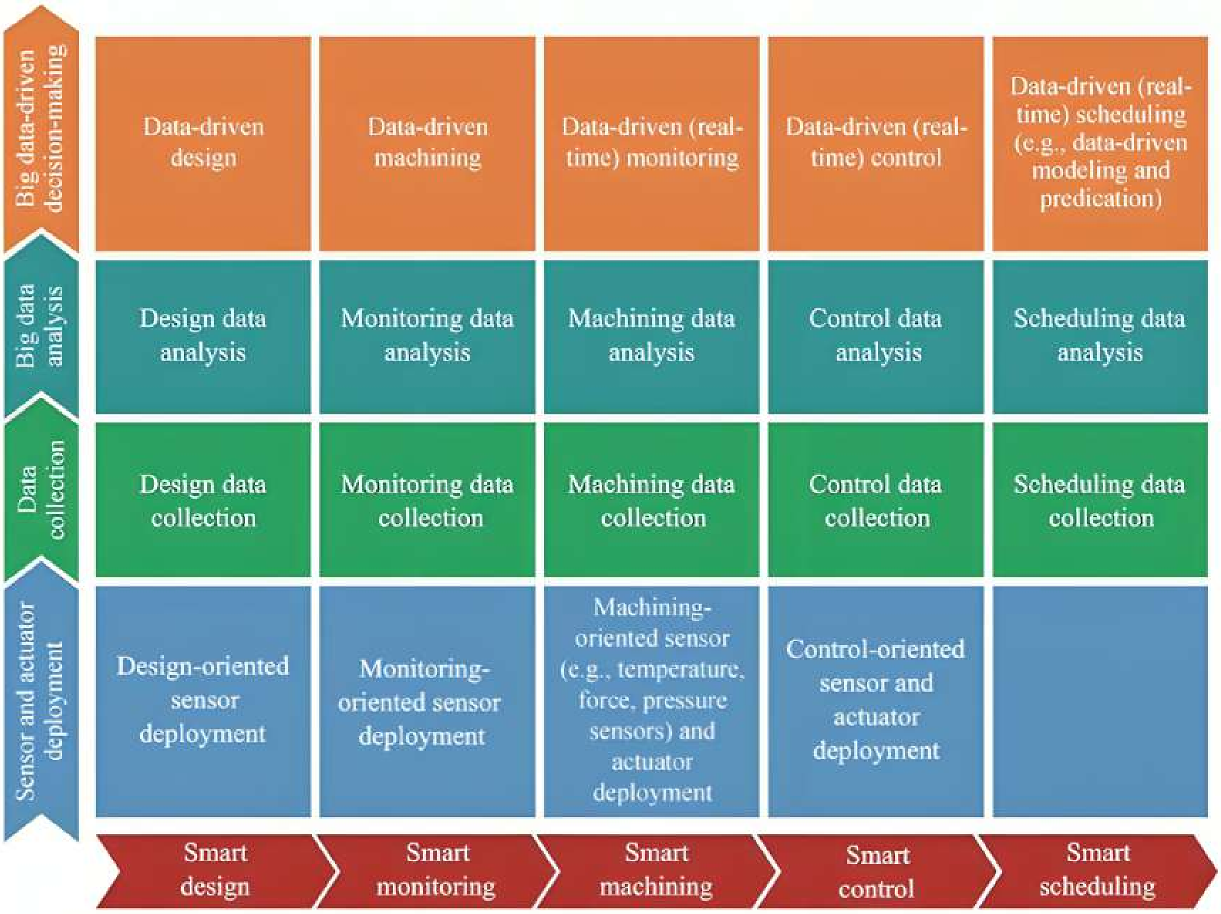


Figure 2.3: Conceptual framework for Industry 4.0 smart manufacturing systems proposed in reference [20]

ated throughout the manufacturing lifecycle. In combination with DTw technologies, they argue that such an approach can be made more responsive, adaptable, and predictive, ultimately assisting companies in becoming more competitive by harnessing knowledge and insights extracted from big data.

Lu et al. [37] delved into the connotation, reference model, applications, and research issues of DTw-driven SM. They emphasize the widespread adoption of intelligent technologies like BDA and AI, which extract real-time manufacturing intelligence. This collective intelligence leads to the evolution of intra-business operations, inter-business collaboration, and production models, promoting smart production, connected production networks, and mass personalization. In line with this perspective, DTw for manufacturing assets, people, factories, and production networks can be created in SM environments. They suggest that future research should prioritize standards, communication protocols, time-sensitive data processing, and reliability in exploring DTw application scenarios.

NIST has notably emphasized the pivotal role of standards in steering the evolution of SM

[96, 97]. Their holistic conceptualization of an ecosystem for SM, spanning three dimensions throughout the manufacturing lifecycle—product, production system, and business—is illustrated in Figure 2.4. This comprehensive approach involves not only presenting a landscape of current standards but also actively contributing to the development of essential frameworks [96, 97, 98]. NIST is deeply engaged in initiatives such as the creation of a DTh for SM [99], ensuring seamless connectivity and information flow throughout the entire product lifecycle. Additionally, their efforts extend to defining product standards specifically tailored for the SM domain [100]. Research contributions from NIST are pivotal in shaping a standardized and interconnected landscape crucial for the success of SM implementations.

At this juncture, it is essential to highlight that the goal of SM is to transform data collected throughout the product lifecycle into manufacturing intelligence, intending to positively influence every facet of the manufacturing process [101]. In this context, effective data management becomes paramount, and it is here that the concepts of DTh and DTw play a pivotal role. The DTh aspires to establish a digital lifecycle ecosystem that interconnects the data produced across a product's lifecycle [102]. It serves as a comprehensive representation of the data, processes, and communication platform supporting a product and its production at any given moment [102]. Simultaneously, DTw provide a virtual representation of physical assets, enabling real-time monitoring, analysis, and optimization. Therefore, the synergy between these concepts becomes the backbone of SM.

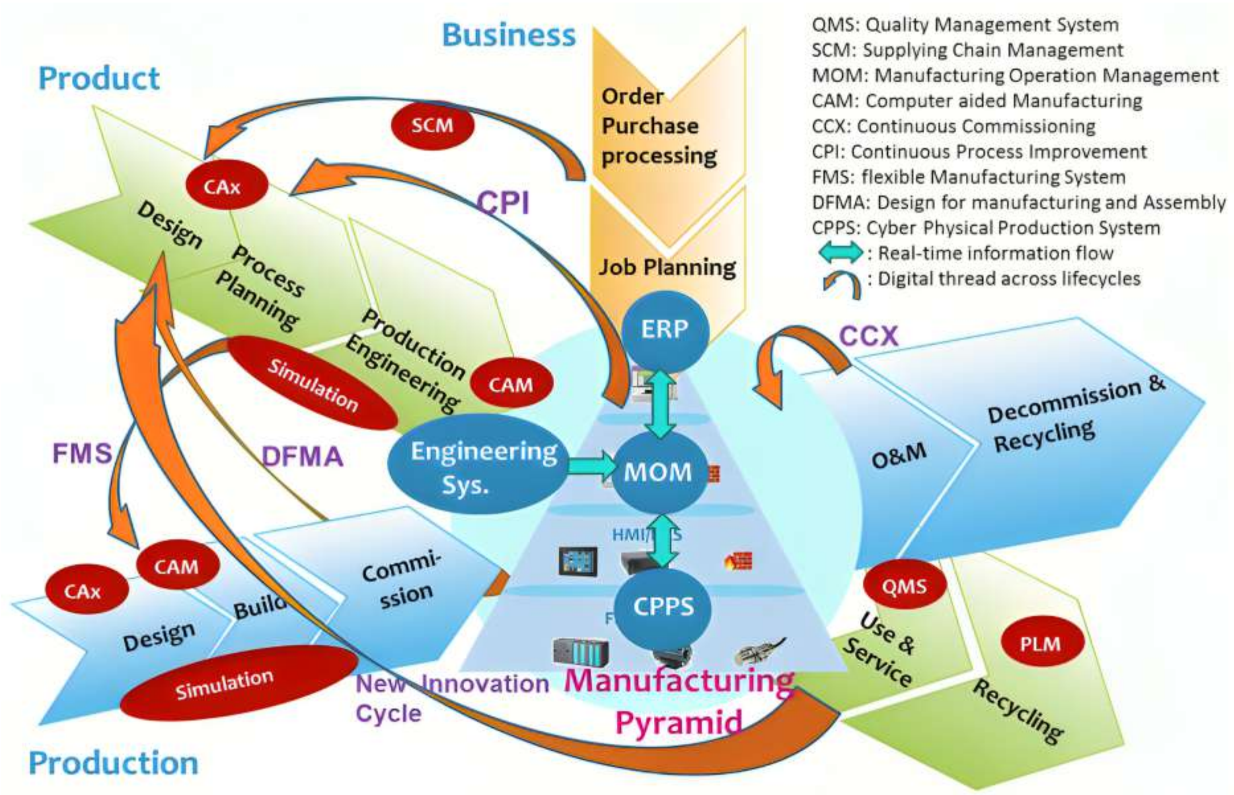


Figure 2.4: NIST's conceptualization of a ecosystem for SM [96].

2.3 Cyber-Physical Systems (CPS)

CPS represent a transformative paradigm at the intersection of physical processes and computational capabilities. These systems seamlessly integrate real-world entities with advanced computing and communication technologies, creating a symbiotic relationship between the physical and digital realms. CPS merge the tangible aspects of the physical world, such as sensors, actuators, and machinery, with the intelligence and connectivity afforded by digital systems. This integration enables unprecedented levels of monitoring, control, and automation across diverse domains, revolutionizing how we interact with and manage the physical world. In the context of SM, CPS play a pivotal role in orchestrating intelligent, interconnected processes that drive efficiency, responsiveness, and innovation throughout the entire manufacturing lifecycle.

The foundation of CPS lies in longstanding principles, demonstrated by early automotive systems integrating physical control with embedded computers since the 1970s [103]. In 2006, the National Science Foundation (NSF) officially coined the term CPS, recognizing the increasing complexity of systems beyond traditional IT representation [36]. Expanding on this, in 2008, Edward A. Lee [33] presented a widely accepted definition for CPS, characterizing them as "integrations of computation and physical processes, with embedded computers and networks monitoring and controlling physical processes, often through feedback loops where physical processes impact computations and vice versa". Today, CPS is universally acknowledged as a pivotal technological component driving the ongoing evolution of Industry 4.0 [18, 86].

By fusing computing, communication, and control in a symbiotic alliance referred to as the “3C” , CPS offer instantaneous sensing, information feedback, dynamic control, and a spectrum of additional services [104, 105]. La et al. [106] propose a 3-tier architecture for CPS (see Figure 2.5): Environmental Tier (physical devices and target environment), Control Tier (monitored data processing and service invocation), and Service Tier (computing environment with deployed services). This service-based CPS offers advantages such as reusing generic services, adapting services to monitored contexts, and flexible handling of functional requirements.

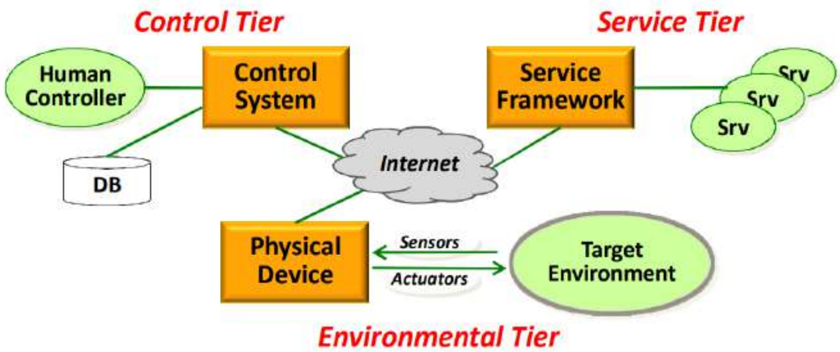


Figure 2.5: 3-tiers architecture of service-based CPS [106].

On the other hand, Lee et al. [107] proposed a 5-level architecture, namely the "5C" architecture, for developing, implementing and deploying CPS in manufacturing. The architecture serves as a practical guideline for enhancing product quality and system reliability. The key levels include Smart Connection (acquiring reliable data), Data-to-Information Conversion (processing data for valuable insights), Cyber Level (central information layer for data analytics), Cognition Level (producing comprehensive knowledge for user decision support), and Configuration Level (supervisory control for machinery adaptability). This approach emphasizes seamless data acquisition, self-awareness in machines, user-friendly presentation of knowledge, and a feedback loop for self-adaptive machinery control. Meanwhile, Jiang [108] advocates the "8C" architecture, an enhancement of the "5C" model, incorporating "3C" facets—coalition, customer, and content. This emphasizes a harmonious blend of vertical and horizontal integration for implementing CPS in smart factories.

The technological core of CPS lies in DTw, a concept that will be thoroughly examined in Section 4. Presently, CPS technology pervades a diverse array of applications, encompassing agriculture, defence, energy response, air transportation, critical infrastructure, health care, intelligent transportation, robotic services, and smart manufacturing [109, 110]. Notably, within the manufacturing sector, the implementation of CPS gives rise to CPPS, which are described in detail below.

2.3.1 Cyber-Physical Production Systems (CPPS)

The integration of CPS into production management has resulted in the emergence of CPPS, representing the fusion of intelligent technologies within manufacturing processes. As delineated by Monostori [34], CPPS represents systems of systems, characterized by cooperative and autonomous elements that establish connections across all tiers of production. This connectivity spans from shop floor processes and individual machines to comprehensive manufacturing and logistics networks. Notably, CPPS facilitates decentralized decision-making in real-time, enabling more agile responses to unforeseen situations and evolving conditions.

CPPS marks a departure from the traditional automation pyramid (illustrated in Figure 2.6), introducing decentralization with a focus on maintaining control and field levels for critical processes. This shift challenges the established hierarchy in manufacturing, allowing computational elements to embed deeply into various devices for decentralized and flexible operation [34]. Emerging from systematic CPS implementation, CPPS represents the future of manufacturing, featuring end-to-end ICT integration and key components for real-time data acquisition, analytics, and self-optimizing production control. This transformative trend underscores CPPS's pivotal role in reshaping industrial production dynamics.

Monostori et al. [109] highlight three key characteristics inherent to CPPS. First, intelligence, or smartness, denotes their capacity to autonomously gather information from the environment.

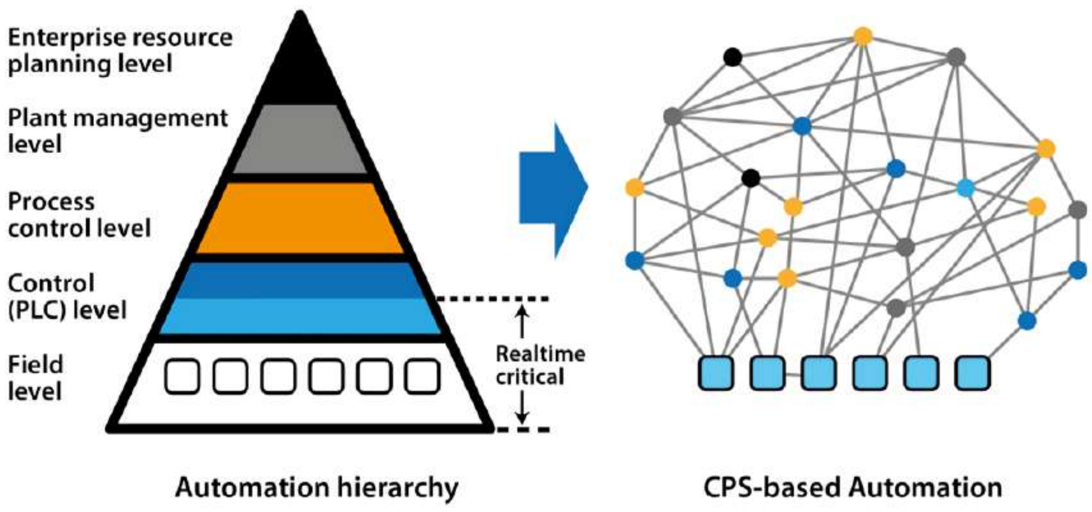


Figure 2.6: Decentralizing the traditional automation pyramid: A breakdown of the automation hierarchy through distributed services [34].

Second, connectedness underscores their proficiency in establishing and utilizing connections with diverse system elements, enabling collaboration with humans and access to internet-based knowledge and services. Finally, responsiveness stands out as a defining attribute, indicating CPPS's adaptability to internal and external changes, ensuring a dynamic and effective operational framework. Ensuring real-time synchronization between physical entities and virtual models is crucial for optimal performance and seamless integration within manufacturing processes, particularly in the context of DTw.

Uhlemann et al. [111] have tackled issues in contemporary manufacturing planning, shedding light on the substantial time investment—74%—dedicated to data acquisition and layout development. Recognizing the underutilization of fully automated techniques in line with Industry 4.0 principles, the authors address deficiencies in automated data acquisition and analysis, particularly in benchmarking results. Their proposed solution involves a pragmatic multi-modal data acquisition approach, coupled with the introduction of the DTw concept. This innovative approach aims to optimize production processes in real-time, emphasizing the integration of CPS for immediate data alignment with the real-life model. The authors further contribute practical guidelines for implementing the DTw in the production systems of small and medium-sized enterprises.

Lu and Ju [112] have introduced the cyber-physical manufacturing services (CPMS) concept in a Service-Oriented Architecture (SOA) framework, leveraging IoT technology. Their model segregates service provision and request aspects, utilizing standardized taxonomies and a reference ontology for mediation, exemplified in a 3D printing use case. Rossit et al. [113] emphasize real-time decision-making, distinguishing basic scheduling issues from higher-level production planning within CPPS for Industry 4.0. Ding et al. [114] delve into CPPS and Digital Twins for real-time monitoring, simulation, and prediction on the shop floor to amplify production efficiency and flexibility. Francalanza et al. [115] introduce a proactive design methodology for CPPS, implemented in a prototype digital factory tool, showcasing its effectiveness in decision support and stakeholder awareness.

The continued investigation into CPPS promises to unlock unprecedented capabilities, fostering a new era where real-time decision-making, flexibility, and enhanced production efficiency converge harmoniously. The imperative of real-time data access is central to CPPS, particularly in the context of Industry 4.0's smart factories. The convergence with IoT further magnifies transformative possibilities, providing the groundwork for exploration in the following section.

2.4 Internet of Things (IoT)

The term "Internet of Things" originated in a 1999 presentation by Kevin Ashton at Procter & Gamble (P&G), linking RFID in supply chains to the Internet [116]. Ashton foresaw a future where computers, with RFID and sensor technology, autonomously gather information about the physical world. This vision aimed to reduce waste, enhance efficiency, and revolutionize our interaction with the environment. The IoT, evolving over two decades, has transformative potential, extending beyond simplistic comparisons like a "bar code on steroids" to revolutionize our world, similar to the impact of the Internet itself [116].

IoT is defined as a global network where interconnected objects, uniquely addressable and employing standard communication protocols, form a dynamic infrastructure with self-configuring capabilities [117]. In this network, physical and virtual "things" possess identities, physical attributes, and virtual personalities, seamlessly integrating into the information network. The fundamental concept of the IoT revolves around enabling communication between entities regardless of location or time, facilitated by context-aware application [118]. This extension of human-computer interaction involves entities capable of being identified and integrated into communication networks, fostering autonomy and context-awareness.

Today, IoT has become a ubiquitous force permeating various sectors and reshaping the technological landscape. Its influence extends in diverse fields application such as healthcare, agriculture, smart cities, and notably, the manufacturing industry [119, 120]. In manufacturing, IoT plays a central role, providing a seamless network that connects devices and systems. This interconnected framework facilitates the real-time exchange of data, laying the groundwork for intelligent decision-making and heightened operational efficiency. Its integration into manufacturing processes stands as a testament to its profound impact on Industry 4.0 and the evolution of smart factories.

IoT transforms manufacturing systems by creating a global network of interconnected "things" that include various components such as materials, sensors, controllers, and machines [121]. The rapid expansion of IoT-driven sensing generates vast datasets, whether stored locally or in the cloud, paving the way towards a CPS-based manufacturing systems. For that, IoT harnesses diverse smart sensing technologies such as RFID (Radio Frequency Identification), wireless sensor networks, and mobile computing [121]. RFID enhances tracking and identification capabilities, while wireless sensor networks provide real-time data from various sources. Mobile computing acts as a catalyst, facilitating seamless integration and accessibility of information, collectively contributing to the robust sensing infrastructure within IoT applications.

Various IoT architectures have been proposed by researchers, reflecting the diversity in this field. A fundamental three-layer architecture comprises the perception layer (physical sensors), the network layer (device connectivity), and the application layer (service delivery) (see Figure 2.7 (A)). However, IoT research has spurred more detailed architectures, such as the five-layer model (see Figure 2.7 (B)). In this expanded structure, the transport layer facilitates seamless data exchange through networks, while the processing layer, or middleware, handles storage and analysis using technologies like databases and cloud computing. Although this description omits the role of the business layer in system management and user privacy, it highlights the intricate and evolving nature of IoT architectures.

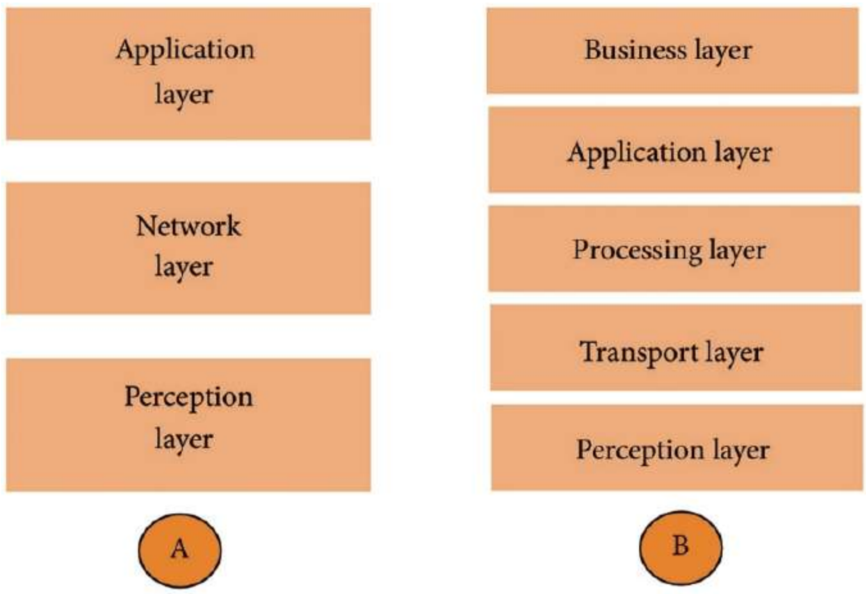


Figure 2.7: Fundamental IoT architectures: (A) Three layers; (B) Five layers. [122].

Other domain-specific architectures have also been proposed to cater to specific areas, encompassing domains like RFID, service-oriented architecture, wireless sensor networks, supply chain management, industry, healthcare, smart city, logistics, connected living, big data, cloud computing, social computing, and security [123].

Ultimately, IoT facilitates a symbiotic interaction between the physical and virtual worlds, enabling ubiquitous connectivity and interaction among people and "things" across various paths, networks, and services. Now, let's delve into the IIoT as a crucial application of IoT specifically tailored for the manufacturing and production industry.

2.4.1 Industrial Internet of Things (IIoT)

IIoT represents a specialized facet of IoT, tailored for modern industries and smart manufacturing within the landscape of Industry 4.0. IIoT, distinct from typical IoT devices, targets significant industrial assets, linking engines, power grids, and sensors to the cloud through a specialized network [124]. This approach resonates with the notion that the Industrial Internet or IIoT encompasses numerous interconnected devices with communication software. These systems and their individual components can monitor, collect, exchange, analyze, and autonomously respond to information, intelligently influencing their behavior or surroundings—without human intervention [124].

This intricate system integrates various technologies synergistically to create a unified, efficient network of systems and devices. By leveraging services, networking technologies, sensors, and middleware, IIoT enhances insight and facilitates monitoring and control of enterprise processes and assets. Its applications play a crucial role in optimizing manufacturing operations, enabling real-time responses through decentralized analytics, and ultimately elevating overall efficiency and productivity. IIoT, with its potential to reduce unplanned downtime, accelerate time-to-market, and enhance economic growth, stands at the forefront of transformative advancements in industrial settings [120].

Now, we delve into an integral IIoT architecture framework shaping the connectivity and intelligence within industrial systems.

2.4.1.1 Industrial Internet of Things Reference Architecture (IIRA)

Other relevant reference architecture for Industry 4.0 is the Industrial Internet of Things Reference Architecture (IIRA), which represents a comprehensive framework designed to guide the integration and implementation of the Industrial Internet of Things (IIoT) [125]. Developed by the Industrial Internet Consortium (IIC), a global organization dedicated to advancing the adoption of the Industrial Internet, the IIRA serves as a foundational blueprint for creating interoperable and secure IIoT systems. This architecture encompasses key aspects such as connectivity, data processing, and security, providing a structured approach for designing and deploying IIoT solutions across various industrial domains.

This architecture is characterized by five functional domains as shown in Figure 2.8: business, operation, information, application, and control, all converging in a data-analysis-centered integration approach. Emphasizing cross-industry versatility and interoperability, the IIRA provides a comprehensive set of methods and models to guide system design, with a strategic focus on deriving tangible business value [126]. Some prior studies [88] have explored mapping and integrating the cross-domain and interoperability strengths of the IIRA with the connected manufacturing value chain focus of the RAMI 4.0. Functional domains of IIRA align seamlessly with RAMI 4.0's vertical layers, specifically addressing asset digitization [88]. This collaborative examination aims to enhance interoperability and provide a more holistic approach to guide the evolution of industrial systems, shaping the future landscape of interconnected industrial ecosystems for Industry 4.0.

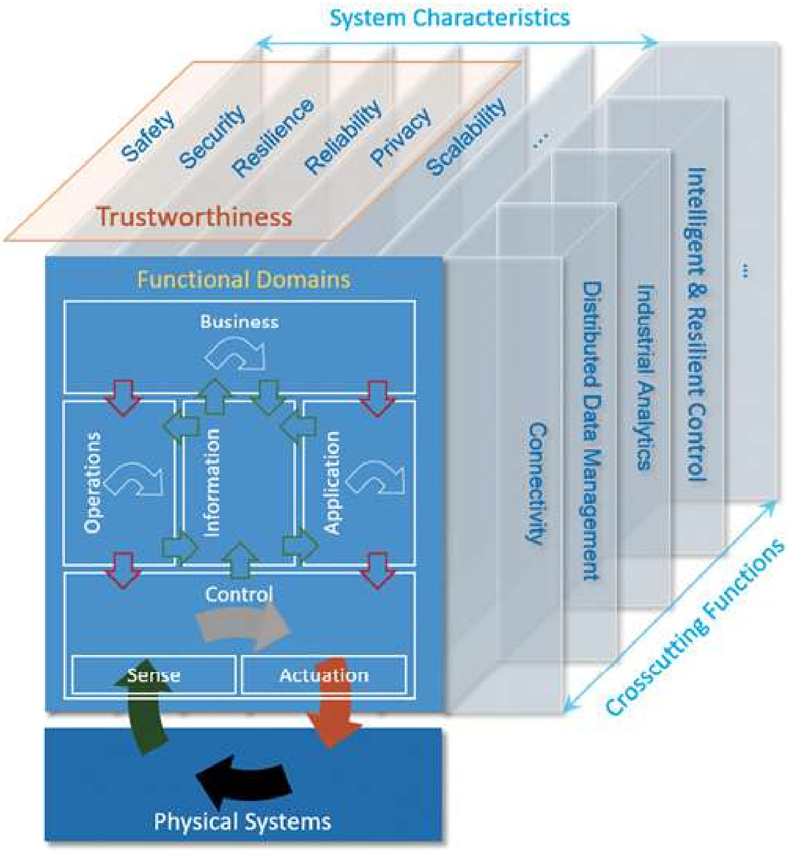


Figure 2.8: Industrial Internet of Things Reference Architecture (IIRA) [125]

2.5 Enabling standard technologies and frameworks

Lu et al. [127] argue that the successful implementation of smart manufacturing hinges on seamless integration within and across manufacturing processes and systems. This integration critically depends on standardized and interoperable interfaces spanning the various stages of manufacturing and phases of the product DTh. Their study highlights key standards pivotal to each phase of the product lifecycle, as illustrated in Figure 2.9. In the design phase, standards like STEP AP203 [128], AP214 [129], AP242 [130], and the QIF model-based design [131] take center stage. For the planning-for-manufacturing phase, they emphasize the importance of STEP-NC (ISO 14649 [132] and ISO 10303-238 [133]), RS-274 [8], and ISO 6983 [9] (G-code). In the planning-for-inspection phase, DMIS [134] and QIF plans [131] are identified as critical standards. During the manufacturing phase, MTConnect [135], OPC UA [136], and ISO 23247 (Digital Twin framework for manufacturing) [137] emerge as key enablers. Lastly, for the inspection phase, QIF results [131] are highlighted as a prominent standard. Moreover, Lu et al. [127] stress that the widespread adoption, dissemination, and continuous evolution of these standards, guided by a demand-driven approach, are essential to realizing the automation of personalized, product-centric manufacturing processes and the development of networked, self-organizing manufacturing systems.

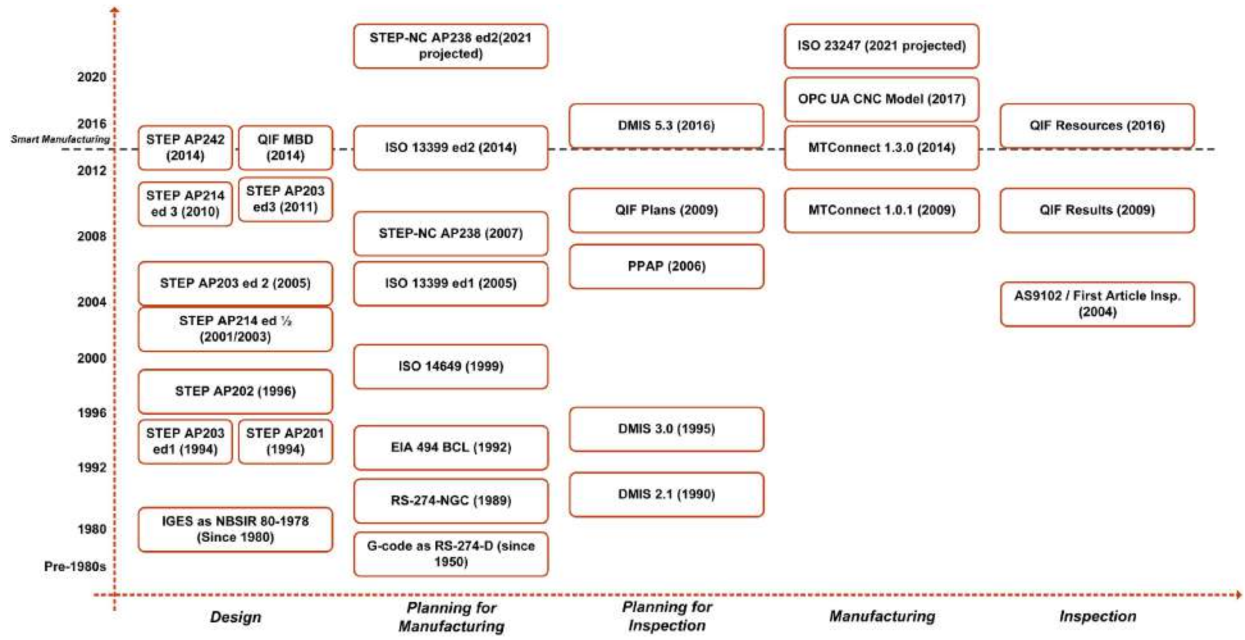


Figure 2.9: Chronological representation of standards across various stages in the product lifecycle [37, 127].

Effective communication among IoT devices relies on standardized protocols that ensure seamless connectivity and interoperability within networks. Yang et al. [121] highlight commonly used data link protocols for IoT systems, including Bluetooth, ZigBee, Z-wave, WiFi, NFC, Sigfox, Neul, LoRaWAN, and Cellular, as detailed in Table 2.2. Additionally, they provide an overview of major IoT platforms that form the foundational infrastructure for seamless communication and integration between physical systems and cyber-world applications. Prominent platforms such as GE Predix, PTC ThingWorx, IBM Watson, Azure IoT, Google IoT Cloud, AWS IoT, Machineshop, Cisco IoT Cloud, and Oracle Cloud support diverse functionalities, including cloud computing, embedded systems, augmented reality, data management, software applications, machine learning, and analytical services, demonstrating their critical role in modern IoT ecosystems.

Table 2.2: Wireless communication protocols with associated parameters. Adapted from [121].

Protocol	Standard	Frequency Range	Data Rates	Range
Bluetooth	Bluetooth 4.2	2.4GHz	1Mbps	50-150m
ZigBee	IEEE802.15.4	2.4GHz	250kbps	10-100m
Z-Wave	ZAD12837	900MHz	9.6/40/100kbps	30m
WiFi	IEEE 802.11	2.4GHz, 5GHz	150 600Mbps	50m
NFC	ISO/IEC 18000-3	13.56MHz	100 420kbps	10cm
Sigfox	Sigfox	900MHz	10 1000bps	30-50km (Rural), 3-10km (Urban)
Neul	Neul	900MHz	10 100kbps	10km
LoRaWAN	LoRaWAN	Various	0.3-50 kbps	15km (Rural), 2-5km (Urban)
Cellular	GSM / GPRS / EDGE, UMTS / HSPA, LTE	900MHz, 1800MHz, 1900MHz, 2100MHz	Varies	35km (GSM), 200km (HSPA), 35-170kbps (GPRS), 120-384kbps (EDGE), 384kbps-2Mbps (UMTS), 600kbps-10Mbps (HSPA), 3-10Mbps (LTE)

The communication protocols listed in Table 2.2 are general-purpose solutions designed for a wide range of IoT applications. However, in the manufacturing domain, specialized protocols have emerged that not only utilize but also integrate several of these foundational protocols. These protocols, including MTConnect, OPC-UA, and MQTT, are increasingly being adopted as open and standardized solutions tailored for industrial environments. Their growing prominence underscores their importance in fostering interoperability and real-time data exchange in smart manufacturing systems. A detailed discussion of these protocols will be provided in subsequent sections.

Based on the literature analysis, a selection of standards has been identified to address various aspects of this ecosystem, including frameworks for cyber-physical systems, DTw frameworks for manufacturing, communication protocols, and data models for information exchange across the DTh. These standards are presented in the following sections.

2.5.0.1 ISO 23704 - Cyber-physically controlled smart machine tool systems

The recently released ISO 23704 series [138], introduced in 2022, plays a pivotal role in standardizing the reference architecture for Cyber-Physical Machine Tools (CPSMT), focusing on both subtractive and additive manufacturing processes. Recognizing the critical role of machine tools in manufacturing, especially in producing machine parts across various industrial sectors, this standard addresses the need for coherence amid the diverse concepts and terminologies employed by different stakeholders in the smart machine tool landscape.

In the context of Industry 4.0 and smart manufacturing, where digitalization and connectivity are paramount, ISO 23704 provides a comprehensive framework for the development and control of cyber-physically controlled smart machine tool systems. The overrall structure of the ISO 23704 is depicted in Figure 2.10. The series encompasses an overview and fundamental principles (ISO 23704-1) [138], a reference architecture for subtractive manufacturing (ISO 23704-2) [139], and a reference architecture for additive manufacturing (ISO 23704-3) [140].

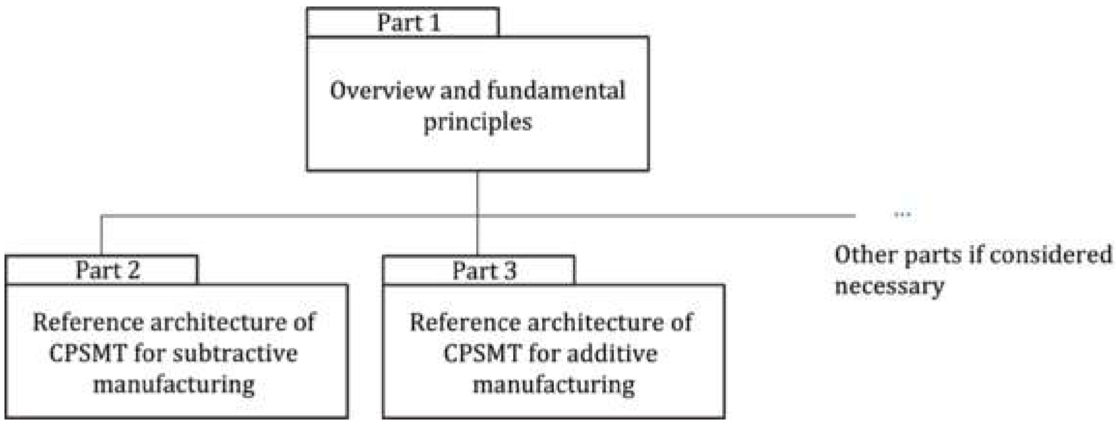


Figure 2.10: Overall structure of the ISO 23704 [138].

The overall structure of ISO 23704 serves as a guide for smart machine tool design engineers, system architects, software engineers, machine tool control vendors, solution and service providers, and end-users. It addresses the general requirements of smart machine tools, supporting smart manufacturing on the shop floor through a cyber-physical system control scheme. As Industry 4.0 continues to evolve, the ISO 23704 series stands as a foundational document, providing a standardized approach to enhance interoperability, efficiency, and reliability in smart machine tool systems. Future additions to the series, including implementation guidelines and reference architectures for different manufacturing types, are anticipated to further enrich its scope and applicability.

Cyber-Physical Machine Tools (CPMTs) represent a transformative leap in smart manufacturing, integrating CNC machines, manufacturing processes, and Cyber-Physical Systems (CPS) under the paradigm of Machine Tool 4.0 (MT 4.0) [7]. Equipped with Machine Tool Digital Twins

(MTDTs)—dynamic digital representations of machine characteristics and behaviors—CPMTs leverage CPS, IoT, and cloud computing to achieve high connectivity, adaptability, real-time interaction, and predictive intelligence [141]. These capabilities enable seamless integration within the digital chain (CAD/CAPP/CAM/CAI) and foster self-aware, autonomous operations, essential for the interconnected and adaptive factory environments envisioned in Industry 4.0 [142].

Advancing the digitalization and servitization of machine tools, Liu et al. [143] reviewed platforms enabling standardized communication among machine tools, highlighting innovations such as a cyber-physical platform based on OPC UA and MTConnect [144]. This approach facilitates interoperable data exchange and showcases applications like augmented reality-assisted interfaces to enhance production efficiency. Similarly, Alvares et al. [145] developed a CPS framework incorporating MTConnect, OPC-UA, and STEP-NC for real-time CNC turning center monitoring and teleoperation. Collectively, these advancements underline the importance of integrating CPMTs with interoperable protocols and data standards to elevate efficiency, process quality, and human-machine collaboration in smart manufacturing ecosystems.

2.6 Communication protocols

Standard communication protocols play a crucial role towards a digital ecosystem powered by DTh and DTw, facilitating seamless interoperability and data exchange across diverse systems and platforms. By adhering to standardized protocols such as MTConnect, OPC-UA, and MQTT, it can effectively communicate with various components, devices, and software applications, enabling real-time data streaming, monitoring, and control. These standardized protocols ensure compatibility, reliability, and scalability, laying the foundation for robust and interconnected digital ecosystems that drive innovation and efficiency across industries. This section delves into the foundations of MTConnect, OPC-UA, and MQTT.

2.6.1 MTConnect

MTConnect, developed by the Association for Manufacturing Technology (AMT) [135], is an open-source and royalty-free communication standard designed to enhance interoperability between shop floor devices and software applications. This standard facilitates data reporting through the Internet Protocol, utilizing prevalent technologies such as XML and HTTP (HyperText Transfer Protocol). At its core, MTConnect consists of two main components: the MTConnect Adapter and the MTConnect Agent. The Adapter serves as a translator, collecting data from shop floor devices, converting it into a simple text-based format, and delivering it to the Agent. Meanwhile, the Agent receives the data, formats it into an MTConnect XML stream, and makes it accessible to web clients in the manufacturing cloud. By utilizing a hierarchical semi-structured data model, MTConnect enables the grouping of data items from manufacturing equipment into readable schemes, accessible to both computers and humans. The Agent responds to HTTP requests by providing XML data streams, offering various request types such as "probe," "current," and "sample" to retrieve different types of data from manufacturing equipment. Figure 2.11 show the data flow in MTConnect-based manufacturing architectures.

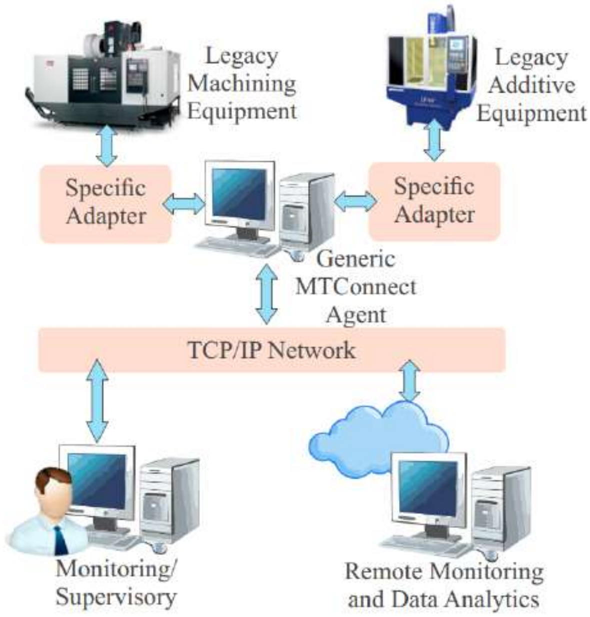


Figure 2.11: A typical data flow in MTConnect-based communication [146]

Moreover, MTConnect defines a semantic vocabulary for manufacturing equipment, ensuring structured and contextualized data exchange without proprietary formats. Leveraging standards like XML, HTTP, and TCP/IP, MTConnect maximizes interoperability and simplifies the implementation of MTConnect-compliant applications. Additionally, MTConnect establishes a hierarchical information model for machine tools, defining components, available data, and their relationships, reducing the effort and time required for building information models and enhancing the usability of MTConnect-compliant applications.

2.6.2 OPC-UA

OPC Unified Architecture (OPC UA) [136] is an open standard protocol designed for industrial communication, serving as a successor to the previous OPC protocol. Unlike its predecessor, which was limited to Microsoft Platforms, OPC UA was developed to be cross-platform, web-based, and independent of specific operating systems. Released in 2006, OPC UA addresses shortcomings of classic OPC, such as platform dependence, inadequate data models, and security concerns. Figure 2.12 shows a basic OPC UA communication architecture.

With a service-oriented architecture, OPC UA offers enhanced security features and supports a broader range of industrial equipment and systems, making it suitable for communication be-

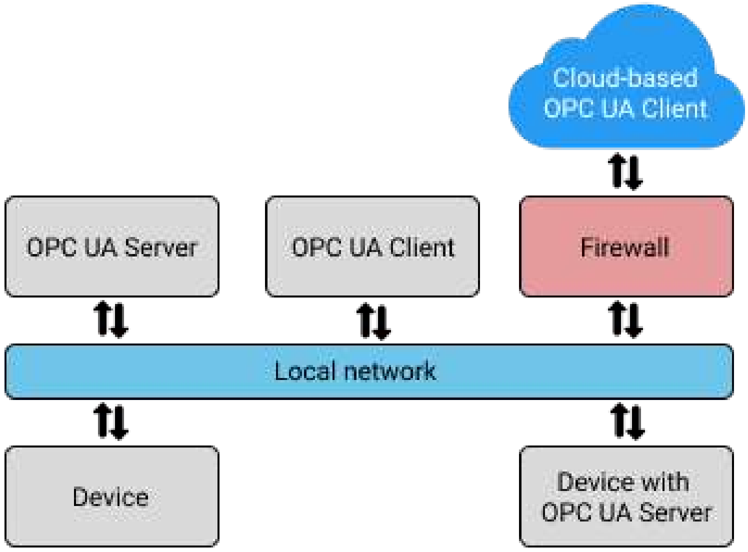


Figure 2.12: Basic OPC UA communication structure

tween devices within machines, between machines, and from machines to systems. This protocol provides both communication and information modeling capabilities, allowing the modeling and development of DTw for manufacturing equipment in the cyberspace.

In the context of Industry 4.0, OPC UA plays a crucial role in CPPS architecture. It aligns with the recommendations of RAMI 4.0, providing standardization for Industry 4.0 communication layers. OPC UA implementation for Industry 4.0 is partially standardized as an international standard IEC 62541 [147], further solidifying its importance in modern industrial communication architectures.

2.6.3 MQTT

MQTT, or Message Queuing Telemetry Transport, is a lightweight and efficient messaging protocol designed for connecting IoT devices. Originally developed in 1999 by Andy Stanford-Clark of IBM and Arlen Nipper of Arcom (now Cirrus Link), MQTT was created to enable minimal battery loss and bandwidth usage when connecting with oil pipelines via satellite [148]. Over time, MQTT has evolved into a widely adopted protocol for IoT and IIoT applications due to its simplicity, reliability, and scalability.

The protocol operates on a publish/subscribe messaging model (See Figure 2.13), where devices publish messages to topics and other devices subscribe to those topics to receive messages. Topics are hierarchical strings that organize messages into logical categories, allowing for flexible communication between devices. MQTT's lightweight nature minimizes the resources required by clients and network bandwidth, making it ideal for constrained environments and low-power devices. One of the key components of MQTT is the MQTT Broker, which acts as an intermediary between publishers and subscribers. The broker receives messages published by devices and forwards them to subscribers based on their topic subscriptions. This decoupling of producers and consumers enables highly scalable solutions and eliminates dependencies between devices.

MQTT offers several advantages, including bidirectional communication, scalability to support millions of devices, and different Quality of Service (QoS) levels to ensure reliable message delivery. It also supports persistent sessions, allowing for the maintenance of connections between devices and servers over unreliable networks. Additionally, MQTT provides security features such as TLS encryption for message confidentiality and authentication protocols for client verification. In 2014, MQTT became an officially approved OASIS (Organization for the Advancement of Structured Information Standards) standard, further solidifying its status as an open and vendor-neutral protocol. After, in 2016, is officially standardized as ISO/IEC 20922 [149]. The latest version of MQTT, MQTT 5, introduced new features for improved reliability and scalability, catering to the evolving needs of IoT applications deployed on cloud platforms and mission-critical use cases.

In general, MQTT's simplicity, efficiency, and robustness make it a preferred choice for connecting IoT devices and enabling real-time communication in a wide range of applications, including smart homes, industrial automation, agriculture, healthcare, and transportation.

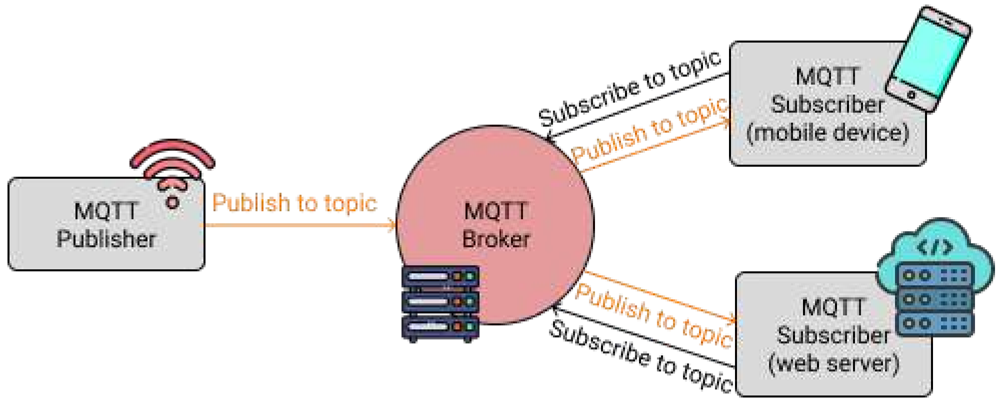


Figure 2.13: Typical MQTT publisher/subscriber architecture. Adapted form [148]

2.7 Manufacturing processes

Manufacturing processes, essential for material transformation, involve diverse techniques that shape raw materials into functional products. These processes play a pivotal role in industry and economic development, impacting product quality, cost-effectiveness, and innovation. Classification of these processes is based on their approach to material transformation, including subtractive (i.e. machining), additive (i.e. AM/3D printing), joining (i.e. welding), dividing (e.g.

sawing,...), and transformative (e.g. forming, heat treatment,...) techniques [150]. It's noteworthy that AM, our primary focus, falls within the additive category, and will be further described below.

2.8 Additive Manufacturing (AM)

AM, commonly known as 3D printing, refers to a revolutionary set of technologies that add material to create 3D physical objects directly from digital models. The ISO 52900 standard define AM as the "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" [151]. Additionally, terminologies such as Rapid Prototyping (RP), Direct Digital Manufacturing (DDM), Rapid Manufacturing (RM), Rapid Tooling (RT), and Solid Freeform Fabrication (SFF) are often used interchangeably to describe AM processes.

Thanks to its unique layer-by-layer material addition concept, AM technologies enable the construction of parts with highly intricate geometries (e.g., lattice structures, mold cooling channels, etc.) without the need for expensive tools or fixtures, thereby minimizing material waste. Furthermore, AM offers unprecedented opportunities for crafting customized, complex parts, whether produced individually or in small batches, suitable for prototyping or immediate use [152, 153]. Its versatility is manifested in its ability to realize products that were traditionally assembled from various components as a single piece, incorporating multiple materials and colors. This not only reduces manufacturing time and complexity but also allows different part groups to be manufactured simultaneously on the same machine without the need for multiple setups, contributing to resource optimization and decreasing production times and costs [154].

Recent advances in materials, process parameters, and machine utilities have propelled AM beyond its initial role in rapid prototyping. It has evolved into a primary manufacturing process, standing alongside traditional methods like machining and incremental sheet forming. This evolution has broadened the scope of AM, making it a viable option for producing functional parts. The technology not only offers intricate design freedom but also provides a higher degree of customization, meeting the dynamic demands of the market for specialized and tailor-made components. The promising benefits of AM have driven its adoption across critical industries, including aerospace [155, 156], automotive [157], biomedical [158], and construction [159]. Simultaneously, its market potential is significant, with an anticipated global economic impact reaching USD $250 billion by 2025 [160].

2.8.1 Primary AM application areas

The application AM in the industry encompasses four production domains, as illustrate in Figure 2.14, each described below:

- **Rapid prototyping**: AM facilitates the creation of low-cost physical prototypes, closely resembling the final product, to swiftly validate solution principles during the conception and design phases of a new product [161]. According to Bruder [162], there are four reasons for utilizing AM in rapid prototyping: first, it accelerates product development by initiating the marketing process earlier; second, it enhances communication among different departments involved in the development process; third, it allows testing functionalities and/or interactions with other components; and fourth, virtual models lack the same visual and emotional perception as a physical prototype.
- **Re-manufacturing**: AM provides possibilities for remanufacturing and repairing parts directly at the end of their life cycle, eliminating the need for the recycling phase. Repaired parts can be reintegrated into the original product or incorporated into a new one, leading to substantial reductions in repair times, for instance, up to 60% for components like industrial compressor turbine parts [163]. Remanufacturing with AM promotes more sustainable manufacturing by markedly decreasing energy consumption and material waste [164], aligning with the principles of a circular economy [165].
- **On-demand parts**: AM tackles challenges linked to maintaining a relatively extensive inventory of parts near consumption sites, including high storage costs, stock obsolescence, and capital costs associated with low-movement parts [166]. Moreover, it effectively addresses the challenge of promptly and cost-effectively providing missing or repair parts to sustain the reliable functionality of products. Through on-demand part production, AM eliminates the necessity for intricate maintenance inventories, proving particularly advantageous in the aircraft spare parts sector [167].
- **Direct-use rapid manufacturing**: Recent advancements in AM, marked by the integration of high-performance materials and enhanced machine capabilities, have propelled it beyond its initial role in rapid prototyping. AM has evolved to directly manufacture parts for final use, promoting the development of innovative, high-performance components and products with novel features. Simultaneously, this evolution results in reduced processing times and production costs.

Different application areas involve various data types, requiring meticulous orchestration. The challenge is to synchronize this wealth of information, ensuring smooth integration—a pivotal aspect in guiding the manufacturing life cycle through a unified DTh.

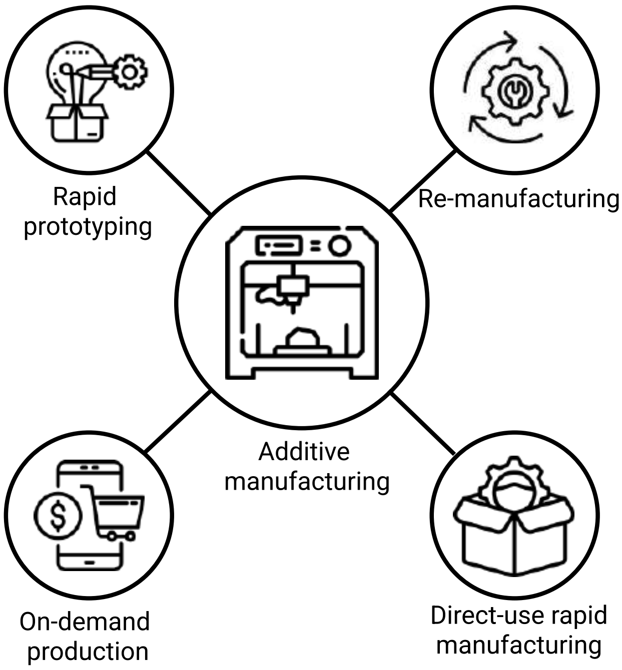


Figure 2.14: Production domains of the AM processes.

2.8.2 Classification of AM processes.

ISO 52900 categorizes AM processes into seven groups [151], considering the type of material and technology employed in the material transformation process, as illustrated in Figure 2.15. These categories include Binder Jetting Technology (BJT), Directed Energy Deposition (DED), Material Extrusion (MEX), Material Jetting Technology (MJT), Powder Bed Fusion (PBF), Sheet Lamination (SHL), and Vat Photopolymerization (VPP).

The categories marked with the label "Metal" indicate processes suitable for metal materials. Within these processes, DED is an innovative AM method that employs focused thermal energy to selectively melt and fuse material layer by layer, constructing intricate three-dimensional structures [168]. Utilizing a precise energy source, like a laser or electron beam, directed at a substrate, localized melting occurs, as shown in Figure 2.16. Simultaneously, feedstock material, typically in powder or wire form, is introduced into the molten pool, solidifying and progressively building the desired object. DED stands out for its versatility in using various materials, making it suitable for producing large and complex components with enhanced material properties.

One specific variant within the DED category is Laser Metal Deposition (LMD). In LMD, a laser is employed to melt and fuse metal powder or wire onto a substrate, layer by layer, creating intricate structures [170]. Meltio [171], a notable player in this field, has pioneered advancements in LMD technology, particularly focusing on wire-based solutions. Meltio's expertise in developing LMD systems with wire feedstock has contributed to the versatility and efficiency of the process, showcasing the potential for this technology in various industrial applications.

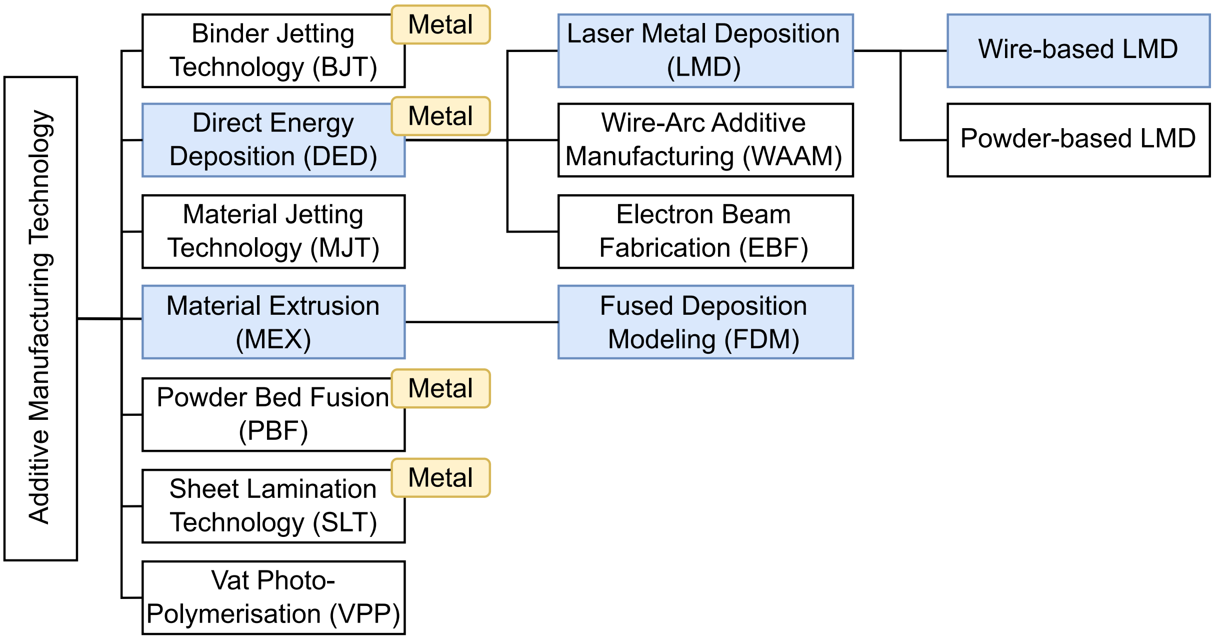


Figure 2.15: Overview of AM technology categories.

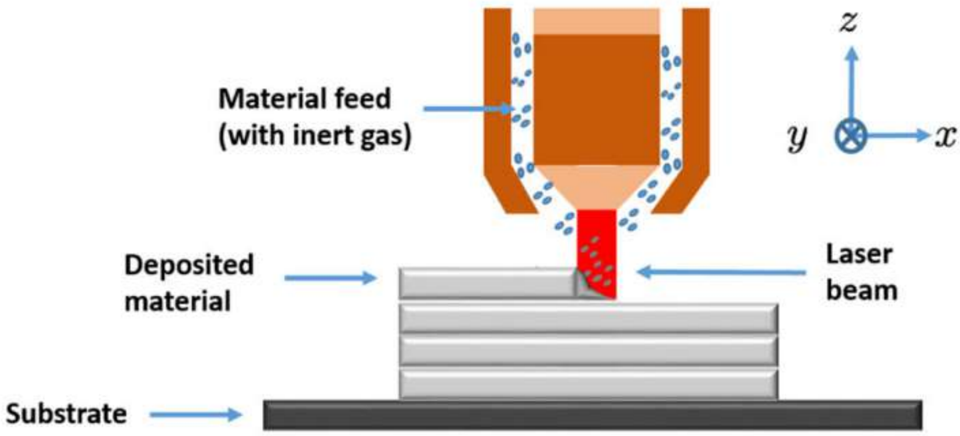


Figure 2.16: Directed Energy Deposition (DED) [169]

Meltio sets itself apart in the realm of DED through its state-of-the-art technology, notably the multi-laser deposition system (head + controller), named Meltio M450 [171]. This compact head, as depicted in Figure 2.17, equipped with multiple lasers, stands out for its simultaneous processing of single and dual wires, showcasing remarkable versatility. Key features encompass integrated wire feeds essential for high process reliability, a short distance from feeder to process ensuring precision in wire feeding, a laser calibration method, Shield Gas Ring preventing oxidation near the melt pool, and a control system equipped with sensors for automatic regulation.

On the other hand, MEX is a popular AM method that involves the layer-by-layer deposition

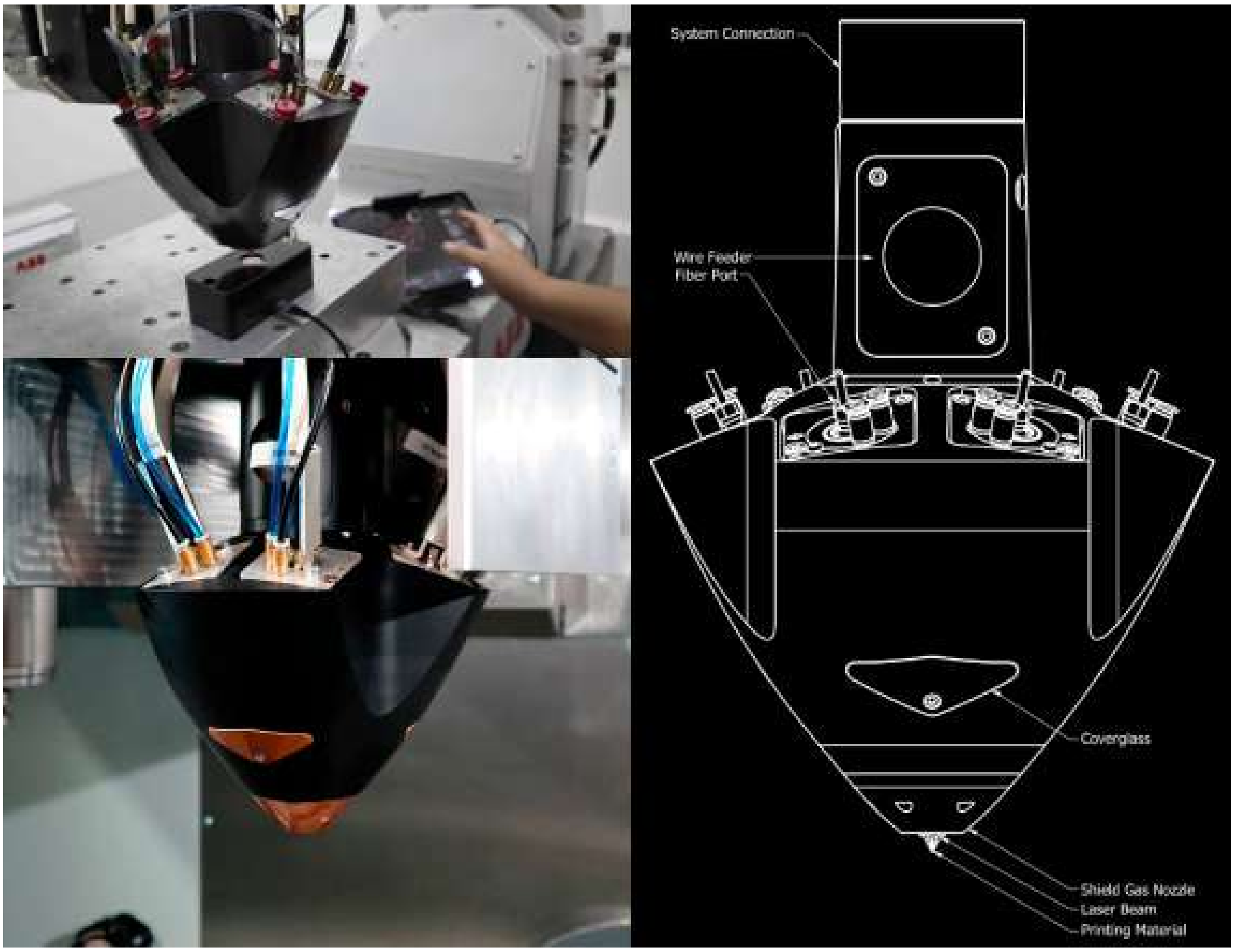


Figure 2.17: Meltio's wire-laser 3D print system for LDM

of melted or extruded material to create three-dimensional objects [172]. This versatile technique, exemplified by Fused Deposition Modeling (FDM) [173], utilizes a heated nozzle to extrude the molten filament with precision, allowing for the construction of intricate designs. FDM, a specific application of Material Extrusion, has become widely adopted for its simplicity, cost-effectiveness, and ability to produce durable prototypes and functional components. It supports various thermoplastic materials, making it suitable for diverse applications in rapid prototyping and customized manufacturing. For a visual representation of the material extrusion process, refer to Figure 2.18.

This work has focus on FDM and wire-based LMD (highlighted in the blue boxes in Figure 2.15), which are technologies actively utilized in research initiatives at our laboratory.

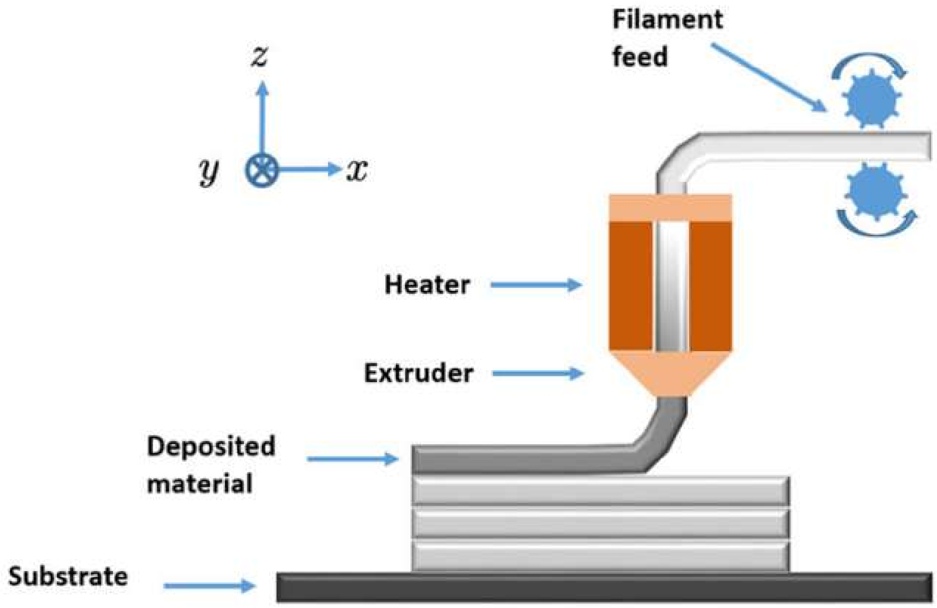


Figure 2.18: Material Extrusion (MEX) [169]

Chapter 3

Digital Thread for Additive Manufacturing: Literature Review

This section delves into the foundational concepts of the DTh, providing a comprehensive understanding of their roles in fostering connectivity and traceability in the manufacturing ecosystem. The exploration extends to the unique advantages brought forth by the DTh in the context of AM processes, while also scrutinizing potential drawbacks that demand innovative solutions for its seamless integration into the contemporary manufacturing landscape.

3.1 Product Lifecycle Management (PLM)

In the midst of the currents of continuous innovation, global collaboration, intricate risk management, and swift technological evolution, enterprises, regardless of size, find themselves compelled to evolve [174]. Unlocking the intricacies of the product lifecycle emerges as a critical compass for businesses, enabling them to adeptly steer through these challenges. Recognizing the dynamic interplay within the lifecycle is not merely an insightful endeavor; it stands as a strategic imperative, empowering enterprises to harmonize with the cadence of change and navigate the complex landscape of modern industry.

Every product inherently follows a lifecycle—conceived, materialized, and ultimately disposed—a succinct sequence of creation, manifestation, and closure. To gain a deeper understanding of this intricate journey, one must navigate through distinct phases visualized in Figure 3.1 as Beginning of Life (BOL), Middle-of-Life (MOL), and End-of-Life (EOL) [175]. The BOL phase incorporates design and manufacturing, where intricate planning and iterative design processes lead to the physical realization of the product within the enterprise's confines. Transitioning to the MOL phase, the product enters the hands of end-users and service providers, navigating through distribution networks and undergoing use and support activities, including repair and

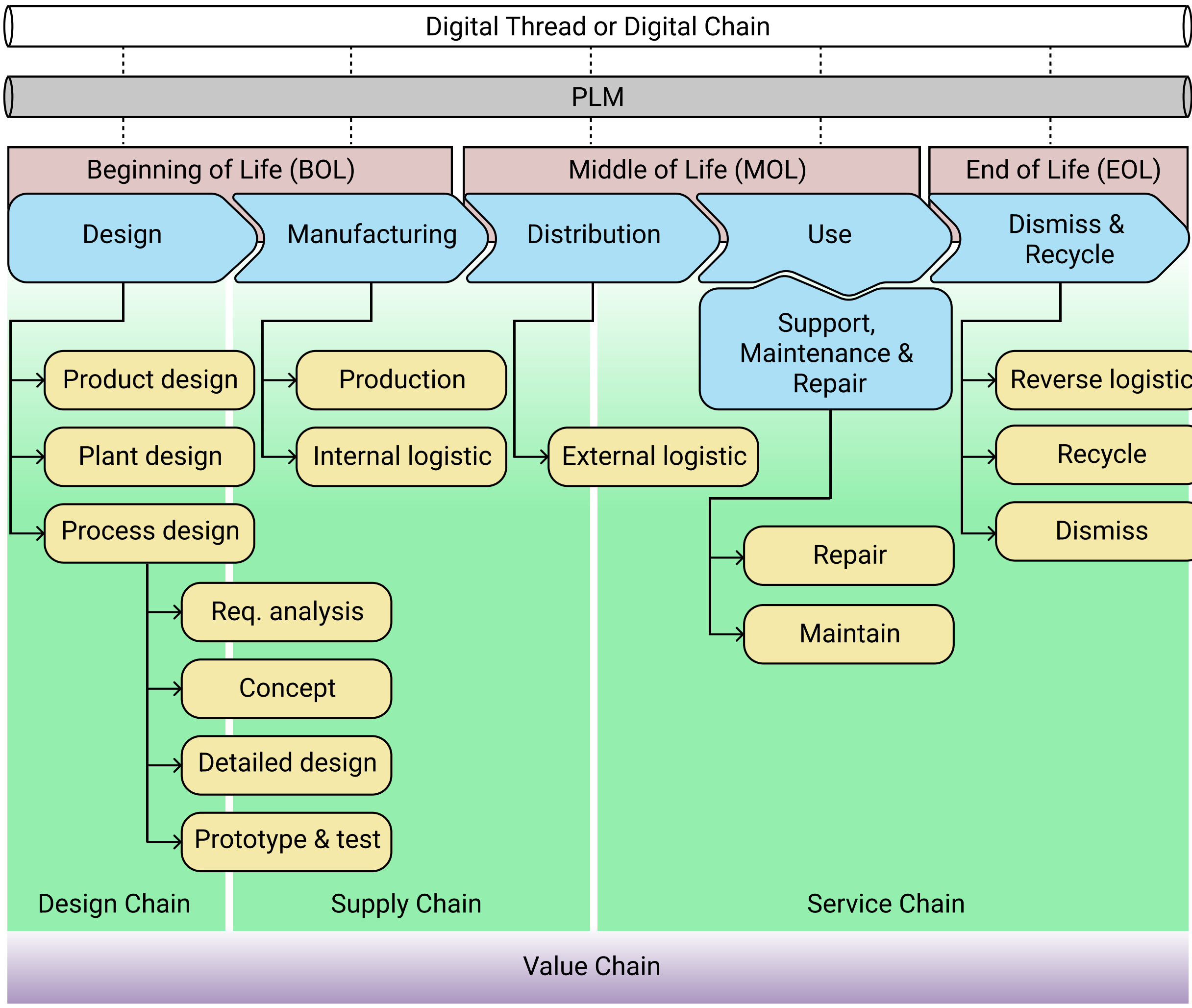


Figure 3.1: PLM and and DTh through product life cycle. Adapted from [175].

maintenance. Finally, the EOL phase marks the product's retirement, initiating reverse logistics for recycling or disposal. Within these lifecycle phases, a data tapestry unfolds—seeds of valuable insights awaiting transformation into actionable intelligence for enterprises.

Effectively traversing the intricate terrain of crafting complex products requires guaranteeing access to product and process information for diverse stakeholders within the value network—partners, suppliers, and customers alike [174, 176]. Tackling this challenge often entails embracing a strategic framework, such as the adoption of a PLM strategy. At the core of PLM lies the sharing and management of information and knowledge throughout the product lifecycle. Corallo et al. [174] define as "a strategic business approach that supports all the phases of product lifecycle, from concept to disposal, providing a unique and timed product data source". Meanwhile, Terzi et al. [175] understand it as a business strategy centered on the product's lifecycle, bolstered by Information and Communication Technologies (ICT).

PLM involves sharing product data among stakeholders throughout various lifecycle phases to ensure optimal performance, collaborative decision-making and sustainability for the product and associated services [175]. Moreover, it represent a unified language for comprehending products, spanning all lifecycle phases from inception to retirement. Chiang et al. [177] have demonstrated how the utilization of PLM frameworks, coupled with business models and strategies, furnishes companies with invaluable reference models to support key activities within the value chain.

Figure 3.1 provides a visual depiction of the all-encompassing value chain that spans the entirety of the product lifecycle, incorporating design, supply, and service chains. PLM operates as a parallel framework to the supply chain, effortlessly sourcing data from every facet of the product lifecycle. This data seamlessly integrates into a concurrent Digital Chain referred to as the DTh, often viewed as the digital manifestation of PLM, adeptly capturing and harmonizing information throughout the entire product lifecycle.

3.2 Digital Thread (DTh)

The inception of the DTh can be traced back to the United States Air Force, where it was defined in the 2013 Global Horizons as a pivotal digital link between materials, design, processing, and manufacturing [178]. Emphasized for its promissory potential, the DTh was recognized as instrumental in ensuring agility and adaptability in the swift development and deployment of weapon systems, while also minimizing risks. Concurrently, in the same year, NIST introduced a parallel definition, describing the DTh as cross-domain, common digital surrogates aiding real-time assessments and informed decisions across the product lifecycle stages [179].

In the context of model-based design (MBD), West and Pyster [178] offer a succinct definition of DTh. Essentially, it represents a framework merging conceptual models of the system, a focal point in Model-Based Systems Engineering (MBSE), with discipline-specific engineering models of various system elements. In this same context, DTh is characterized as a dataset that enables integrating model-based definition, manufacturing, and inspection [180, 181]. According to Hedberg st al. [180], harnessing a range of data and engineering knowledge empowers DTh to perform real-time analysis and dynamic evaluations of project cost, schedule, and performance. This fosters real-time design, collaborative process-flow development, automated artifact creation, and seamless full-process traceability among project participants in collaborative development [182].

Kim et al. [183] define the DTh in the context of AM as the information and its path accumulated and stored during the manufacturing of a single part. This encompassing digital record allows for the comprehensive management and tracking of "what, how, where, who, when, and why" throughout the entire AM process. Similarly, Mies et al. [184] define DTh as the seamless capture and analysis of data throughout the product lifecycle to optimize efficiency and innovation, notably reducing tooling costs and lead times. Likewise, additional investigations have highlighted the DTh's capacity to delineate the cohesive data flow across every phase of naturally digital processes like AM [185, 186].

NIST has been instrumental in advancing the development of the DTh from multiple angles. Helu and Hedberg [187] describe a concept for a product lifecycle test bed built on a cyber-physical infrastructure, enabling research and development in SM. Additionally, Hedberg et al. [188] proposed a method using graphs to form digital threads, linking and tracing data throughout the product lifecycle for improved interoperability in smart manufacturing, aiming to capture a $30 billion annual opportunity.

The NIST SMS Test Bed's vision for the DTh involves connecting data across the as-designed, as-planned, as-executed, and as-inspected stages. This integration is achieved through the utilization of open standards such as STEP AP242, G-code, MTConnect, and QIF, as illustrated in Figure 3.2. Building on this, Kwon et al. [189] draw from this vision to enhance automated methods for product quality assurance. In their work, Kwon et al. address the challenge of a lack of unified information models from design to inspection. Their proposed solution involves fusing as-designed data from STEP and as-inspected data from QIF into a standards-based digital thread using ontology with knowledge graphs. The automated pipeline creates knowledge graphs for STEP and QIF data, integrates them with a mapping implementation, and demonstrates through rules and queries the potential for informed decision-making in product quality assurance.

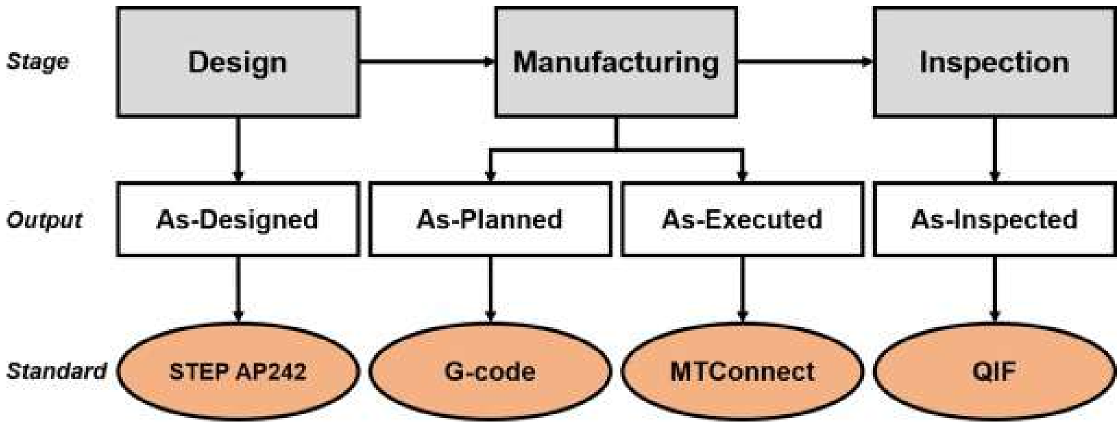


Figure 3.2: The vision of DTh from the NIST SMS Test Bed [189].

Helu et al. [190] devised a four-tiered architecture to address challenges in developing the digital thread. This design effectively manages manufacturing system data, providing segregated access for internal and external clients. The architecture safeguards intellectual property, enables the fusion of manufacturing and product lifecycle data, and has demonstrated practical value in identifying performance improvement opportunities during implementation with a contract manufacturer. Moreover, Helu et al. [191] introduce a pioneering approach that integrates semantically-rich, standards-based connections, linking planned (ISO 6983) to fabricated (MTConnect) product data through dynamic time warping. This enrichment of the digital thread enables designers to

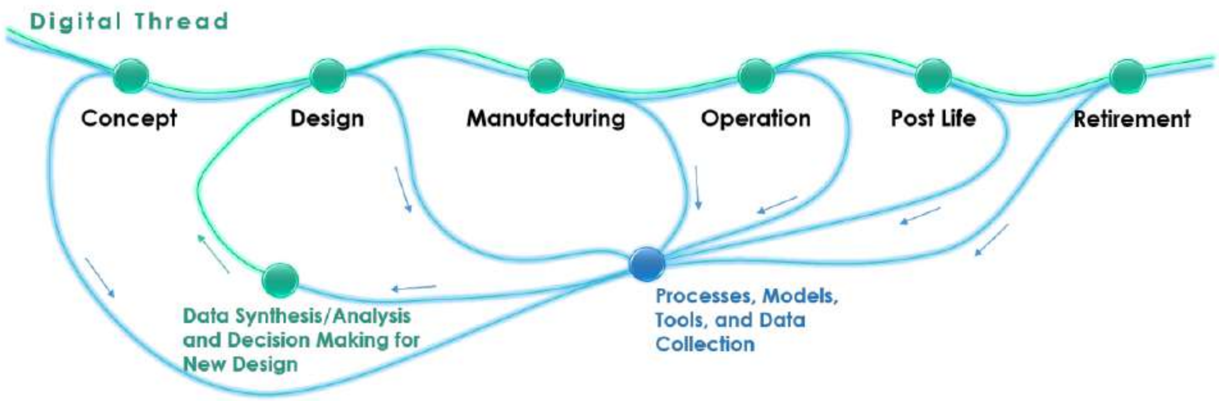


Figure 3.3: Integration of engineering design within the product lifecycle using the DTh [192].

make optimal decisions within the broader product lifecycle, advancing data-driven applications like digital twins.

Singh and Willcox [192, 193] formulated a principled approach to analyze decision-making under uncertainty for the DTh, utilizing Bayesian statistics and decision theory. Their contribution involves addressing uncertainty propagation in the product lifecycle, exploring design decisions over multiple iterations, and providing an algorithm for optimizing decisions in a multistage context, as demonstrated in a structural design problem. Figure 3.3 illustrates multiple the stages across the product lifecycle feeding information into the DTh.

Gharbi et al. [194] introduced STAnDD, a multi-phase design approach for a commercial aircraft, emphasizing Collaborative Engineering and PLM tools. The focus on the wing rib in the initial phase incorporates automatic feature extraction for substantial time savings in the detailed design process. Similarly, Siedlak et al. [195] propose an affordability-based design integrating manufacturing considerations into traditional aircraft design metrics through a DTh approach, demonstrated using a wingbox design problem for early-stage tradespace exploration. Eskue [196] review a DTh for composite aerospace components, noting challenges in consistent connection points and proposing an immediate roadmap for AI-driven insights and manufacturing optimization.

3.3 Research on Digital Thread in AM

To explore the current state of research on the digital thread in AM, a systematic search was conducted in the Scopus database using key terms related to additive manufacturing processes ("additive manufacturing", "3D printing", and "rapid prototyping") and commonly used terms for the digital thread ("digital thread" and "digital chain"). This search yielded a corpus of 70 documents, forming the foundation for this review. The analysis spans publications from 2012, when the concept of the digital thread was first introduced, to the present, highlighting the evolution of this field within the context of AM.

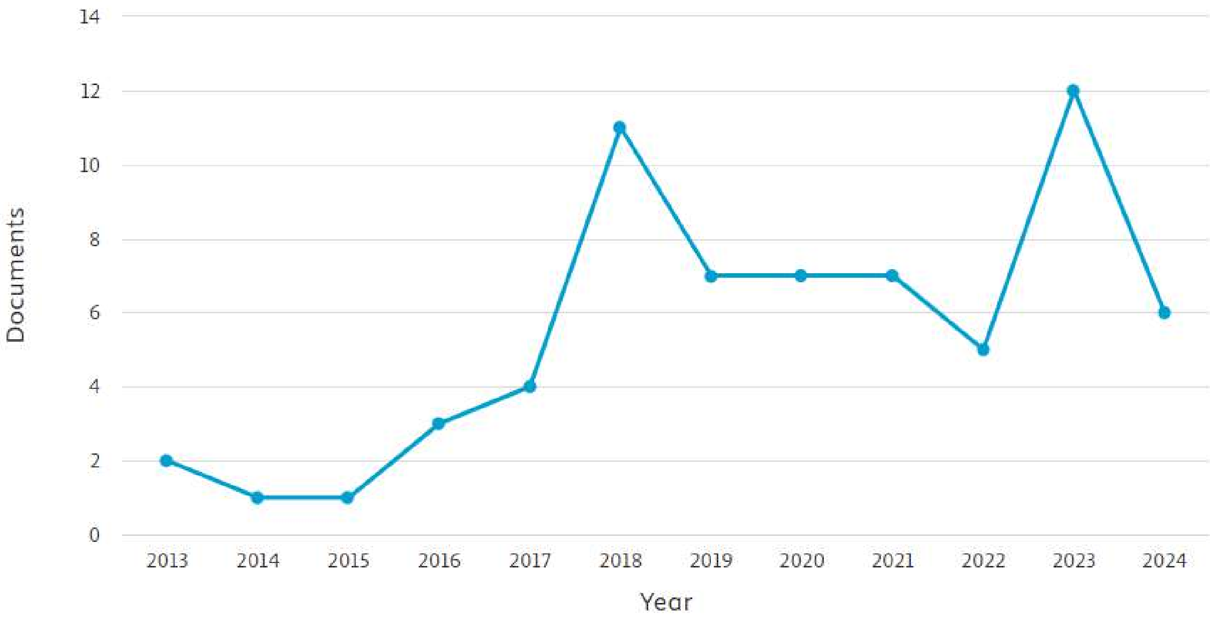
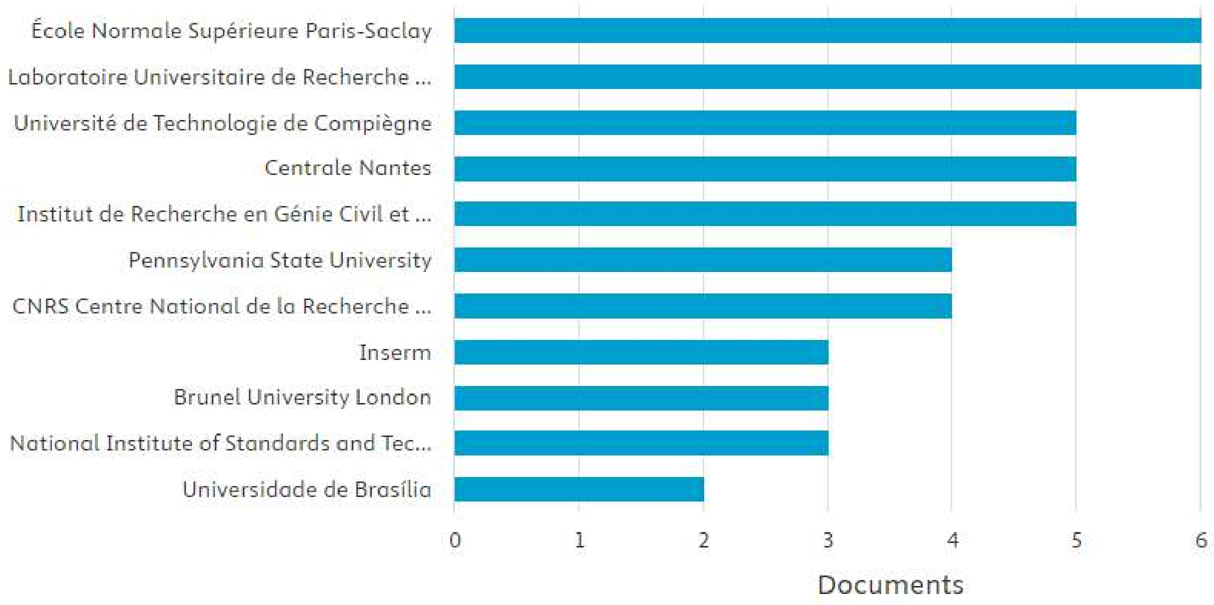


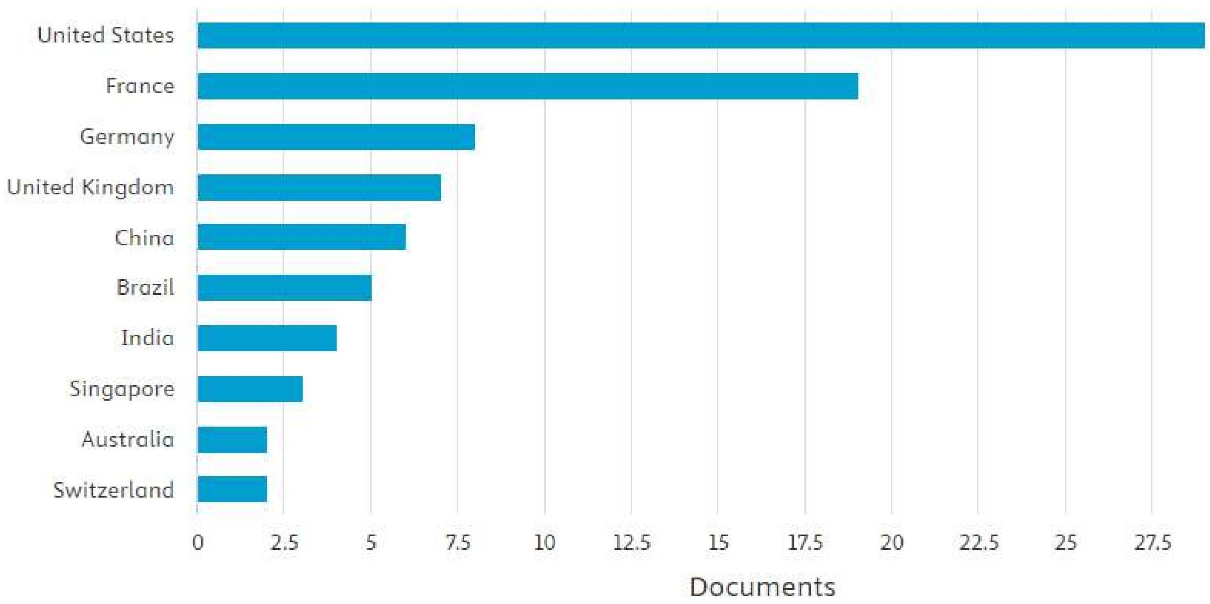
Figure 3.4: Publications by year on Digital Thread in AM using the query TITLE-ABS-KEY ((“additive manufacturing” OR “3D printing” OR “rapid prototyping”) AND (“Digital Thread” OR “Digital Chain”)).

Figure 3.4 shows the distribution of publications by year, showcasing a clear upward trend in research activity. Notable peaks are observed in 2018 and 2023, with 11 and 12 publications, respectively, reflecting growing academic and industrial interest in integrating DTh concepts within AM processes. These peaks may align with the increasing adoption of Industry 4.0 technologies and the emphasis on data-driven manufacturing paradigms.

Figure 3.4 shows the distribution of publications by year, revealing a clear upward trend in research activity on the digital thread in additive manufacturing (AM). Notable peaks in 2018 and 2023, with 11 and 12 publications respectively, reflect growing academic and industrial interest in integrating DTh concepts within AM processes. These surges in research output may correlate with the increasing adoption of Industry 4.0 technologies and the heightened focus on data-driven manufacturing paradigms. Complementing this analysis, 3.5(a) highlights the geographical distribution of publications, with the United States leading the field, followed by France, while Brazil ranks sixth with five contributions. This underscores the global relevance of DTh applications in AM, with significant input from both developed and emerging economies. Furthermore, 3.5(b) focuses on institutional contributions, showing a strong presence of French research organizations but also highlighting the University of Brasília as a notable contributor from Brazil, with two publications on the topic. Both studies involved our laboratory, emphasizing our active engagement in advancing this field.



(a)



(b)

Figure 3.5: Additional statistics from the Scopus database regarding DTh in AM: (a) Documents by country; (b) Documents by affiliation.

Nassar and Reutzel [197] outline AM processes in four succinct phases (blue boxes in Figure 3.6): part design, process planning, execution, and verification. This concise view opens the door to diverse possibilities, revealing intricate details and introducing new activities for a comprehensive lifecycle. Kim et al. [183], for example, consider a total of eight phases (yellow boxes in Figure 3.6), including part geometry/design, raw tessellated data, tessellated 3D model, build

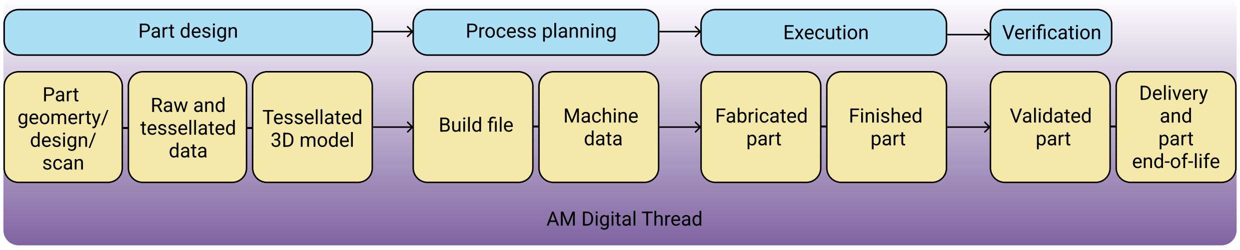


Figure 3.6: Overview of the AM Digital Thread. Adapted from [183, 186, 197]

file, machine data, part, finished part, and validated part. Meanwhile, Bonnard et al. [186], extend these eight phases by incorporating an additional step related to activities of delivery and the end-of-life management of the part (yellow boxes in Figure 3.6).

Every phase within the AM process signifies a distinct stage in the part's lifecycle, providing opportunities for data retrieval. Leveraging this data can extract information and insights, leading to cost and time reductions, improved part quality, process efficiency, and fostering innovation. The process of capturing and analyzing data throughout the lifecycle of AM processes is referred to as the Digital Thread of AM [184]. According to Kim et al. [183], DTh encompasses the collection and storage of information throughout the manufacturing of an individual part, emphasizing interoperability across the supply chain, enhancing digital design and testing capabilities, and reducing costs in various industries. It allows manage and trace information about "what, how, where, who, when, and why" from the entire AM process [183].

The DTh of AM can be seen as a digital journey undertaken by data during the production of a part through an AM process. Imagine this journey as a seamless ride-sharing experience, reminiscent of a sophisticated app like Uber. In this analogy, the DTh assumes the role of a master navigator, orchestrating the flow of information much like the app guides cars through bustling city streets.

In this digital journey, the passengers being transported symbolize the data traveling through the DTh, while file formats serve as the vehicles facilitating their journey. Beyond simple transportation, the data undergoes dynamic changes and updates at each DTh phase, akin to stops in a passenger's journey, offering opportunities for activities or modifications orchestrated by software tools and information systems. Just as a ride-sharing app provides real-time insights on road conditions, weather, or driver availability, the DTh offers valuable feedback and optimizations throughout the process, benefiting all participants involved. Picture this as not merely a digital pathway but a seamless information flow that provides opportunities for optimized resource utilization, better traceability, minimized errors, and enhanced quality control.

Ideally, AM DTh could establish a unified platform for data exchange, where stakeholders can efficiently share information, ensuring a consistent and accurate representation of the part's specifications and requirements. This opens up possibilities to enhance collaboration and communication across the supply chain. That interoperability level not only streamlines the design and production processes but also facilitates quicker decision-making and problem-solving. Furthermore, implementing the DTh in AM enable improved efficiency and reduced costs, while real-time monitoring and analysis of data throughout the entire lifecycle enable better control over the manufacturing process.

However, embracing the DTh in AM is not without its challenges. Ensuring data integration, interoperability, and consistency throughout the interconnected phases of the process remains a paramount concern. Standardizing data formats and protocols is crucial for effective collaboration in the DTh for AM. However, this poses a significant challenge given the diverse range of technologies and software used in the AM landscape. Achieving seamless interoperability requires addressing issues related to data compatibility, security concerns, and the integration of various software systems throughout the AM process. Additionally, ensuring consistent data representation across different stages of the AM lifecycle and aligning diverse stakeholders on standardized practices are essential challenges that need to be navigated for the successful implementation of the DTh in AM.

In the context of Industry 4.0, the requirements transcend conventional manufacturing paradigms, highlighting the essential necessity for interoperability and data integration spanning diverse disciplines and the entire product lifecycle [198]. This extends to fostering collaboration between cyber-physical systems and human-centric elements [198]. As Industry 4.0 champions a SM approach, efficient data management through the DTh becomes crucial. The DTh not only ensures seamless connectivity but also empowers applications like DTw, playing a pivotal role in predictive analytics and process optimizations.

The limitations inherent in the AM DTh underscore the urgent need for transformative solutions in line with the requirements of modern industry and the trajectory toward SM systems. These challenges include the necessity to improve transparency across all DTh phases, eliminate redundancy and information duplication while ensuring modularity and scalability. The achievement of interoperability and bidirectional data flow, particularly in multiprocess manufacturing contexts, emerges as a critical requirement. Overcoming these hurdles is pivotal for seamless interaction among various AM design, materials, and process systems.

Additionally, addressing challenges related to information isolation, redundant data formats, and unidirectional flows is essential for unlocking the full potential of a unified, intelligent digital thread that facilitates closed-loop manufacturing and ensures robust traceability throughout the product lifecycle. Kim et al. [199] underscored the importance of establishing baseline data structures and part provenance through an AM DTh to enhance part producibility, process repeatability, and part-to-part reproducibility. Lipman and McFarlane [200] discuses model-based engineering concepts through existing and emerging standards for part geometry and tolerances contain information related to the AM process. A high-level DTH based on a hierarchical object-oriented model for AM has been proposed by Bonnard et al. [201]. The evolution toward a high-level, neutral data model is imperative to transcend current limitations and propel AM's integration into cutting-edge, data-driven manufacturing paradigms.

Table 3.1 provides a summary of key proposals for implementing DTh in AM. It highlights contributions from various studies, detailing their proposed lifecycle phases, data formats, whether they are reviews or new proposals, and notable aspects of their approach. The table showcases the diversity of DTh concepts in AM, emphasizing the importance of modularity, scalability, interoperability, and traceability across all stages of the AM lifecycle.

3.3.1 Data models and file formats for DTh in AM

Qin et al. [73] conducted a comprehensive analysis and comparative study, qualitatively categorizing more than 20 file formats and data models for 2D and 3D representation in additive manufacturing, inlcuding STL (Standard Tessellation Language), AMF (Additive Manufacturing File), 3MF (3D Manufacturing Format), OBJ (Wavefront Object Format), CLI (Common Layer Interface), and STEP (Standard for the Exchange of Product Data) to name a few. Their evaluation considered crucial aspects, including coverage, accuracy, redundancy, reparability, interoperability, verifiability, extensibility, compatibility, accessibility, and application. Kumar et al. [202] also contributed to this review, providing a comprehensive examination of various 3D model representation file formats and 2D slice formats used in AM systems, offering a comparison based on multiple perspectives in their research. Below are descriptions of some of these formats.

3.3.1.1 STL format

The STL (Standard Tessellation Language) format, developed by 3D Systems in 1987 [203], stands as a widely adopted file format for representing 3D model data in AM. It employs a straightforward tessellation approach, covering a model's surface with planar triangular facets, and has become the de facto standard in the AM industry [73]. The STL format is renowned for its simplicity, requiring standard surface triangulation algorithms, known for their simplicity, accuracy, and robustness, to convert a 3D model into its STL format. This simplicity contributes to its wide-ranging applications, allowing STL files to serve as representation, storage, and exchange formats.

However, despite its widespread use, the STL format has notable drawbacks. The representation includes redundant data, and there's a trade-off between approximation accuracy and conversion efficiency [204]. STL files lack the ability to represent color, materials, and texture, and issues such as truncation errors, inconsistent normals, incorrect intersections, and facet degeneracy can arise during the conversion process. In response to STL format limitations, efforts from researchers involve refining the method or exploring potential replacements [205, 206].

Table 3.1: Summary of Digital Thread proposals for AM.

Reference	Digital Thread	Proposed Formats	Review/Proposal	Key Highlights
[197]	Defines four main AM phases: part design, process planning, execution, and verification.	Not specified.	Proposal	Focus on lifecycle integration through four essential stages.
[183]	Introduces eight AM lifecycle phases, including raw tessellated data and validated part.	STEP, STL.	Proposal	Emphasizes interoperability and data traceability across AM phases.
[186]	Extends Kim's model by including delivery and end-of-life management phases.	Hierarchical object-oriented models.	Proposal	Highlights the need for modularity and scalability in AM DTh.
[184]	Advocates DTh for capturing and analyzing data across AM processes.	Not specified.	Review	Focuses on cost reduction, quality improvement, and innovation.
[199]	Proposes baseline data structures to enhance reproducibility and producibility.	Model-based engineering formats.	Proposal	Addresses part provenance and process repeatability challenges.
[200]	Discusses model-based engineering for AM geometry and tolerances.	STEP AP242, QIF.	Review	Explores existing and emerging standards for integrating AM DTh.
[201]	Proposes a high-level hierarchical object-oriented model for AM DTh.	Object-oriented data models.	Proposal	Aims to overcome current AM DTh limitations with neutral data models.

3.3.1.2 AMF format

The Additive Manufacturing File (AMF) format, established in 2009 as a revolutionary successor to the STL format, marked a significant advancement in the representation of 3D model data for AM [73]. Originally dubbed STL 2.0, it gained official recognition in 2013 as the AMF format and received standardization under ISO/ASTM 52915 (2013) [207]. Subsequent revisions in 2016 further solidified its standing. This standardized approach, endorsed by the International Organization for Standardization (ISO) and ASTM International, positions AMF as a recognized and regulated file format for AM processes. This standardization underscores its importance in providing a consistent and reliable framework for representing intricate details, including geometry, materials, color, and other attributes critical to modern AM applications. Hiller and Lipson [208] highlight AMF format attributes such as simplicity, adaptability, continuous development, user-friendly design, and an inclusive open-source approach that encourages active engagement from the community. Nassar and Reutzel [197] propose this XML(Extensible Markup Language)-based file format to record and transmit data throughout the AM DTh. Despite facing certain challenges, such as issues with normals and slicing [209, 210], the AMF format remains a pivotal advancement, setting a standardized trajectory for the representation of 3D model data in the field of AM.

3.3.1.3 3MF format

The 3D Manufacturing Format (3MF) emerges as a pivotal player in AM, born out of Microsoft's internal development and further refined by the collaborative efforts of the 3MF Consortium [211] . Introduced to address STL interoperability challenges, this XML-based format provides a comprehensive representation of 3D model data, including crucial details like materials, colors, and other specifications. Structured into the 3MF core and materials/properties segments, it employs triangular meshes for geometry representation.

Unlike its predecessor, the AMF format, the 3MF format restricts the use of curved triangles, aiming for a more compact and size-friendly file. Boasting advantages such as completeness, human readability, simplicity, extensibility, unambiguousness, and free access, it seeks to streamline communication between CAD/CAM software and AM systems hardware [73, 211]. Despite its promising features, the 3MF format grapples with challenges concerning widespread adoption and approximation accuracy. While its incorporation into products by various AM-related companies signals a positive trajectory, lingering doubts persist about the extent of its accessibility and implementation within the user community.

3.3.1.4 OBJ format

The OBJ format (.obj) serves as a versatile file format for exchanging 3D graphics among diverse systems. Initially developed by Wavefront Technologies [212] and widely adopted due to its open-source nature and simplicity, OBJ has found significance in AM for facilitating multi-colored and multi-material manufacturing requirements. It currently stands as the second most prevalent representation for 3D model data in the AM industry [73].

Offering the representation of geometry through tessellations with polygons, free-form curves, or surfaces, OBJ supports both ASCII and binary encodings. While tessellations with polygons involve a trade-off between approximation accuracy and file size, the use of free-form curves or surfaces ensures faithful encoding of curved geometries without compromising data. The format allows color and texture data storage in a separate material template library (MTL) file [213], enabling the rendering of intricate, multicolored textured models. Despite its advantages, the OBJ format is more complex than the STL format, posing challenges for repair and editing [73]. Additionally, managing paired MTL files with each OBJ file introduces potential complexities, especially in scenarios with a large number of files.

3.3.2 CLI format

The Common Layer Interface (CLI) format is a dedicated file format designed for 2D slice data representation in additive manufacturing (AM). Developed by the Commission of the European Communities, it offers a simple, efficient, and machine-independent solution for layered manufacturing systems. Each layer is defined by thickness, contours, and optional hatches, providing an unambiguous format for various fabrication machines. While the CLI format can serve as a robust choice for presenting layer data in the slicing phase of the AM DTh, it falls short in representing other crucial information from other phases of the AM DTh.

3.3.3 The need for a high-level data format to support the AM DTh.

Qin et al. [73] present a thorough examination of various data representation formats for AM, extending beyond the formats previously mentioned. The array of formats includes X3D, JT, RPI, STH, CLF, SIF, SPF, PLY, SAT, Non-manifold B-Rep, Feature Tree, CSG, Voxel, Trivariate Spline, LEAF, SLC, CLI, HP-GL language, and MAMF. This review underscores the multitude of formats within the AM domain, posing a challenge in determining the most suitable one to support the comprehensive digital thread of AM. Primarily designed to describe 3D or 2D geometry-related data of a part, these formats occasionally incorporate additional information like textures, color, material, and other attributes. Unfortunately, none of these formats provides a comprehensive data model covering all aspects of a part across the DTh. Persistent challenges such as information loss and ambiguity in data formats for AM hinder the development of an efficient DTh implementation in AM processes.

In this context, Nassar and Reutzel [197] advocate for an AM DTh built upon the extended AMF format, encompassing all data phases of AM processes. To achieve this, they propose four additional file formats augmenting the existing AMF format:

- the Additive Manufacturing Slice File (AMSF), detailing slice information;
- the Additive Manufacturing Path File (AMPF) extension, incorporating data on path planning and process parameters;
- the Additive Manufacturing Qualification File (AMQF), designed for sensor data and as a qualification record; and,
- the Additive Manufacturing Verification File (AMVF), employed in the final stages of the verification and validation phase.

In pursuit of their vision, they advocate using the AMF format, capitalizing on its XML foundation [197]. This choice provides advantages such as self-description, human-readability, simplicity, and widespread use in online data exchange. Additionally, XML's inherent extensibility allows users to tailor tags to their specific needs, enhancing adaptability in their proposed digital thread solution.

On the other hand, a NIST research work [183] discusses the challenges of closed or proprietary architectures in AM and proposes an open federate architecture approach to enhance manufacturing flexibility and agility, which is presented in Figure 3.7. The open architecture allows customization throughout production, supporting the use of new materials and process parameters. The integration of interoperability mechanisms facilitates data exchange between different AM domains. Figure 3.7 illustrates the AM parameters and a solution stack, emphasizing the design-to-product transformation and various mechanisms/enablers for managing information. Additionally, it introduces architecture functions for systems engineering principles in the digital end-to-end implementation of AM processes.

The work further delves into leveraging the proposed architecture for AM opportunities. It highlights the importance of identifying information requirements early in AM part development for informed decision-making. Improved traceability and decision-making are emphasized, especially regarding geometry representation/design rationale. Communication enhancements between design and process stages are suggested to gain insights into process planning, support structure requirements, and post-processing operations. The need for effective process control, predictive modeling, and part qualification is discussed to advance AM capabilities systematically. The proposed closed-loop process control function aims to leverage systematic advances

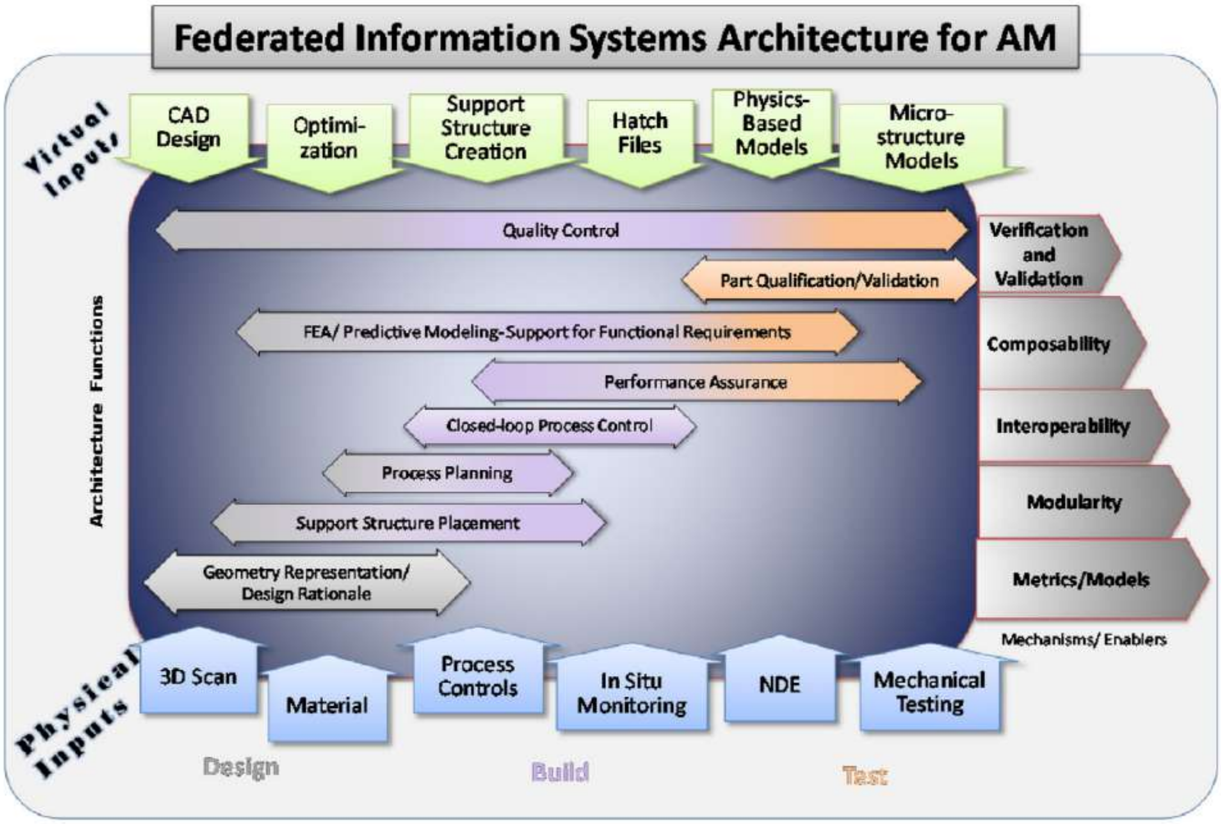


Figure 3.7: NIST's federated information systems architecture for AM [183]

for performance assurance and part qualification, emphasizing the significance of understanding the fundamental physics of process-structure-property relationships in AM [183].

Qin et al. [73] have extensively reviewed and highlighted the STEP format as an integrated solution for representing AM data. Moreover, other authors have echoed the praise for the STEP and STEP-NC format, recognizing it as an excellent means to support a seamlessly integrated high-level DTh for AM [186, 214]. Pei et al.'s research findings indicated that STEP-NC and AMF standards are at the forefront in incorporating the most esteemed features for data transfer, while Xiao et al. [215] highlight STEP as a strong contender to replace other AM file formats due to its support for GD&T management and standardization of product information, ensuring compliance with PMI. The STEP format's comprehensive capabilities position it as a promising candidate for facilitating an interconnected and holistic representation of data throughout the AM processes. Hence, it is essential to explore and elucidate the characteristics of the STEP format and its existing utilization in AM. A comprehensive analysis of the intricacies and current status of the STEP format holds the key to uncovering valuable perspectives on how it could contribute to enhancing the integration and efficacy of AM processes. To facilitate this understanding, an overview of the STEP and STEP-NC standards is provided in Chapter 5.

Chapter 4

Digital Twins for Additive Manufacturing: Literature Review

This section delves into the DTw concept, exploring their definitions, distinctive characteristics, reference architectures in the manufacturing domain, and their specific application in AM processes. This in-depth analysis will provide a comprehensive insight into how these DTw are fundamentally transforming our understanding and approach to modern manufacturing, forging innovative connections between the physical and digital worlds.

4.1 Digital Twins (DTw) concept

DTw stand as a cornerstone among the technological advancements within Industry 4.0, representing an integral component of the CPS. Interestingly, its roots predate the advent of Industry 4.0, with Dr. Grieves introducing the concept in 2003 during his PLM course at the University of Michigan [216]. His proposal lays the foundation for a groundbreaking DTw model that involves the integration of physical products (real space), virtual products (virtual space), and interconnected data, showcasing its visionary potential. A decade later, in 2012, NASA defined DTw as an integrated, multi-physics, multi-scale simulation mirroring the life of an as-built vehicle or system [45].

In the manufacturing context, Tao et al. view the DTw as the bridge between physical and digital realms for smart manufacturing [217]. Meanwhile, ISO 23247 standard defines a manufacturing DTw as a fit-for-purpose digital representation (digital entity) of an observable manufacturing element (physical entity) that is synchronized with each other [137]. Subsequently, a substantial number of definitions of the Digital Twin have been formulated depending on its application domain or its relationship to similar terms such as DTh, Product Avatar, and real-time simulation, as reported in [218].

Tao et al. [36] have meticulously dissected the correlation and distinctions between CPS and DTw, delving into facets like origin and development, physical-cyber/digital mapping, hierarchical model, and implementation functions. In this intricate comparison, CPS emerges as akin to a scientific category, prominently featured in Industry 4.0, while DTw assumes the guise of an engineering category. Despite their unique identities, both concepts converge on the overarching theme of cyber-physical integration, sharing certain technologies to actualize this convergence. They unite in their trajectory toward the realization of SM, marking a transformative journey where science and engineering harmonize for innovative solutions.

Over the years, advancements in IoT, AI, Big Data analytics, and cloud computing have propelled the DTw concept to a more mature and compelling level. Presently, DTw technology has emerged as a versatile solution, finding applications in diverse industries such as aerospace [219, 45], healthcare [46], agriculture [47], smart cities [48], and notably manufacturing [49, 37, 220]. Leading technological companies have played a pivotal role in advancing DTw offerings, with examples including Dassault Systèmes' "3DEXPERIENCE Twin" [41], Siemens' "Teamcenter X" [42], IBM's "Watson IoT Platform" [43], and Microsoft's "Azure Digital Twins" [44]. Within manufacturing, DTw has proven instrumental in product design [221], smart shop floors [222], machine tools [223], and predictive maintenance [224], to name a few.

4.1.1 Characterization of the DTw

Jones et al. [225] have conducted a comprehensive characterization of the DTw, meticulously compiling a total of 12 distinctive features along with their corresponding descriptions, which are detailed in Table 4.1. Barricelli et al. [218], on the other hand, have outlined key communication aspects as integral characteristics of the DTw. These encompass three primary types of communication processes that necessitate thoughtful design:

- Communication between the physical and the virtual twin.
- Communication between the digital twin and other digital twins in the surrounding environment.
- Communication between the digital twin and domain experts who interact and operate on the digital twin through user-friendly and accessible interfaces.

Kritzinger et al. [220] introduce a classification system for DTw based on the extent of data integration between physical and digital counterparts. Within this framework, three distinct subcategories emerge:

- Digital Model (On the left of Figure 4.1): Describing an existing or planned physical object, the Digital Model lacks automated data exchange. It encompasses comprehensive

Table 4.1: Characteristics of the DTw and their descriptions.

Characteristic	Description
Physical Entity/Twin	The physical entity/twin that exists in the physical environment
Virtual Entity/Twin	The virtual entity/twin that exists in the virtual environment
Physical Environment	The environment within which the physical entity/twin exists
Virtual Environment	The environment within which the virtual entity/twin exists
State	The measured values for all parameters corresponding to the physical/virtual entity/twin and its environment
Metrology	The act of measuring the state of the physical/virtual entity/twin
Realisation	The act of changing the state of the physical/virtual entity/twin
Twinning	The act of synchronising the states of the physical and virtual entity/twin
Twinning Rate	The rate at which twinning occurs
Physical-to-Virtual Connection/Twinning	The data connections/process of measuring the state of the physical entity/twin/environment and realising that state in the virtual entity/twin/environment
Virtual-to-Physical Connection/Twinning	The data connections/process of measuring the state of the virtual entity/twin/environment and realising that state in the physical entity/twin/environment
Physical Processes	The processes within which the physical entity/twin is engaged, and/or the processes acting with or upon the physical entity/twin
Virtual Processes	The processes within which the virtual entity/twin is engaged, and/or the processes acting with or upon the virtual entity/twin

representations, such as simulation models for future factories or mathematical models for new products. However, data exchange is entirely manual, with no direct impact between changes in the physical and digital states.

- Digital Shadow (On the middle of Figure 4.1): Expanding on the Digital Model, the Digital Shadow involves automated, one-way data flow from the state of an existing physical object to a digital counterpart. Alterations in the physical object trigger corresponding changes in the digital representation, but the reverse relationship is absent.
- Digital Twin (On the right of Figure 4.1): The DTw achieves full bidirectional data integration between an existing physical object and its digital counterpart. Serving as a controlling instance for the physical object, the digital representation responds directly to changes in the physical state, and vice versa. Furthermore, external objects, whether physical or digital, can induce changes in the digital object's state.

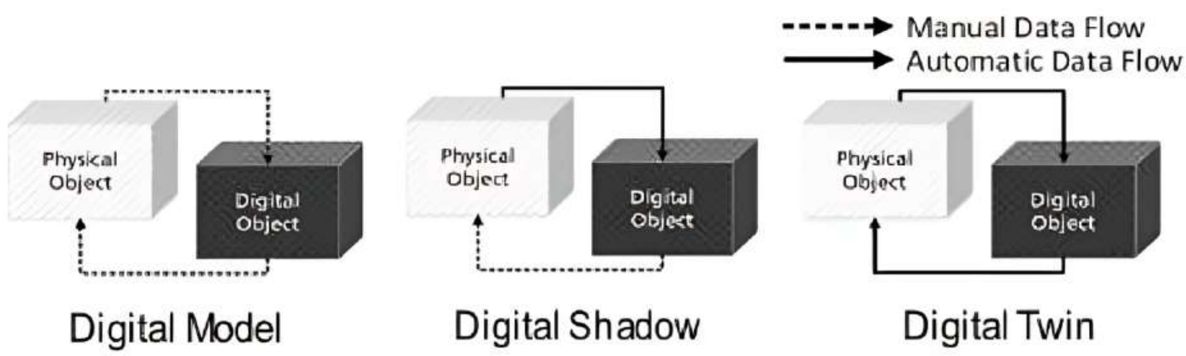


Figure 4.1: Characterization of DTw according to its data integration level [220]

Characterization of DTw lays the foundation for understanding its diverse applications and functionalities. However, seeking standardized frameworks can guide the effective implementation and utilization of DTw across various domains. Therefore, reference models and architectures of DTw are explored in this sequence.

Although the DTw is closely related to the DTh, they represent distinct concepts within the context of modern manufacturing. The DTh focuses on the seamless flow of contextualized data across the entire lifecycle of a product, whereas the DTw serves as a dynamic virtual representation of physical assets or processes, enabling simulation, monitoring, and optimization. Table 4.2 highlights the key differences between these two concepts in terms of origin, definition, concept, and technology.

4.1.2 Reference models of DTw for manufacturing

Due to the pressing need to describe how the interaction between physical assets and their digital counterparts should proceed within the complex dynamic environment of Industry 4.0, several efforts have been made to consolidate a reference model and implementation architecture

Table 4.2: Comparison of Digital Thread and Digital Twin

	Digital Thread	**Digital Twin**
Origin	2013 - Global Horizons, U.S. Air Force	2003 - Dr. Grieves, PLM course at the University of Michigan.
Definition	"Digital Thread a digital linkage between materials, design, processing, and manufacturing that provides the agility and tailorability needed for rapid weapon system development and deployment" - U.S. Air Force, 2013. "... is an integrated information flow that connects all the phases of the product lifecycle" - NIST, 2018	"Digital Twin is an integrated multiphysics, multi-scale, probabilistic simulation of an as-built vehicle or system that uses the best available physics models, sensor updates, fleet history, etc., to mirror the life of the corresponding flying twin" - NASA, 2012
Akin to	Product/process lifecycle digitization	Specific asset/system digitization
Related technological concepts	PLM, MBSE, OOM, SOM, Digital Twins	Cyber-Physical Systems, IoT, Simulation, Surrogate Models

of DTw in industrial production systems. The purpose of a DTw reference model is to guide manufacturers and practitioners on arranging and preparing the technologies, procedures, standards, and best practices that can be used to implement Digital Twins in manufacturing applications.

4.1.2.1 Three-dimensional model

The three-part Digital Twin model, as introduced by Grieves [216], is depicted in Fig. 4.2 (a). This model comprises a physical product existing in real space and its synchronized virtual representation, interconnected through a bidirectional communication channel. Similarly, Lu et al. [37] have proposed a three-component Digital Twin model tailored for the realization of smart manufacturing (refer to Fig. 4.2 (b)): the first component is an information model mapping physical assets and creating abstractions; the second involves a data processing module generating representations of physical assets based on extracted information and knowledge; and lastly, a two-way communication mechanism facilitating interaction between the physical and digital spaces.

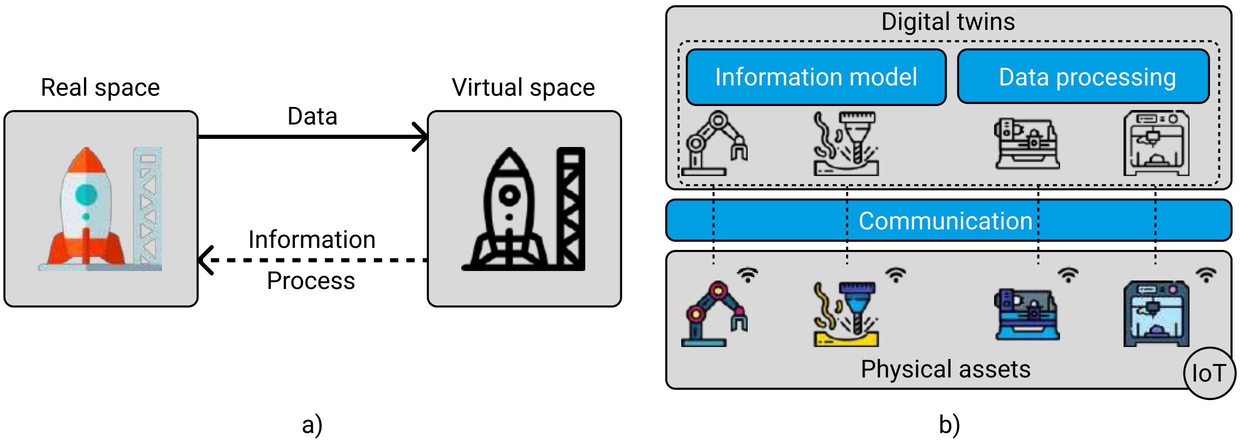


Figure 4.2: Three-dimensional reference models of Digital Twin: a) adapted from [216]; b) adapted from [37].

4.1.2.2 Five-dimensional model

Tao et al. [222] introduced a comprehensive DTw model grounded in five dimensions: physical part, virtual part, services, data, and connections. Their emphasis on the equal importance of each dimension underscores a holistic approach to crafting impactful DTw. The inception of the physical part catalyzes the creation of its virtual counterpart, unlocking a realm of possibilities for simulation, decision-making, and control services. This interconnected ecosystem thrives on the wealth of knowledge derived from data transmitted through the intricate connection mechanism. As the digital and physical seamlessly converge in this model, it not only reflects innovation but also paves the way for a future where DTw redefine the landscape of SM with unparalleled effectiveness.

4.1.2.3 Digital twin framework for machining

STEP Tools, Inc. [54] developed an interoperable DTw framework for machining, showcased in demonstration meetings in 2016 with active participation from Boeing, OMAC, and the ISO TC184/SC4 committee. This groundbreaking framework (see Figure 4.3) facilitates closed-loop machining by integrating real-time inspection data, adhering to DTh standards such as STEP-NC, MTConnect, and QIF. Leveraging the STEP-neutral file format, STEP AP242 and STEP-NC AP238 are employed to encapsulate data related to design, process planning, and inspection. MTConnect contributes by making machine status data accessible over the Internet through REST API, catering to consumption by web clients. Furthermore, QIF serves as the communication channel for relaying inspection results back to the design domain.

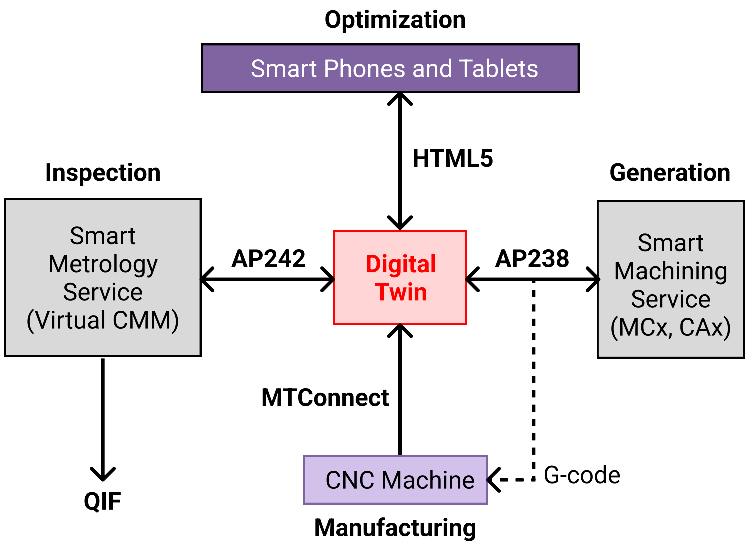


Figure 4.3: Digital Twin framework for machining proposed by STEP Tools, Inc. [54].

4.1.2.4 Other related proposals

Several notable contributions have been made to the field of manufacturing DTw models. A notable study by Alam and El Saddik [226] introduces an architecture reference model of DTw for cloud-based CPS, termed C2PS. This model incorporates a smart interaction controller grounded in a fusion of fuzzy rules and Bayesian networks. On the other hand, Aheleroff et al. [227] propose an architecture reference model for DTw as a Service (DTaaS) within the context of Industry 4.0. They have successfully implemented this reference model in an industrial case, demonstrating its potential benefits in scheduled maintenance, real-time monitoring, remote control, predictive functionalities, and mass individualization. Further insights into DTw models are explored in related proposals, as documented in references [228, 229, 230]. These diverse approaches contribute to the evolving landscape of DTw frameworks in manufacturing, each offering unique perspectives and applications.

4.1.2.5 The ISO 23247 DTw framework for manufacturing

The reference models and architectural frameworks mentioned above are the result of the efforts of the international research community and have paved the way for the development and standardization of a new DTw framework for manufacturing.

The ISO 23247 standard [137], introduced in 2021, represents a significant milestone in the standardization efforts of the ISO committee TC 184/SC 4. The primary aim of this standard is to provide a comprehensive DTw architecture framework tailored for industrial manufacturing applications within the context of Industry 4.0. It offers invaluable guidance on constructing DTw for manufacturing, emphasizing interoperability among systems and the seamless integration of data from diverse sources. The standard comprises four integral parts outlined below. These parts offer guidance on analyzing modeling requirements, setting scope and objectives, using common terminology, specifying a generic reference architecture for instantiating a DTs, and supporting information modeling and synchronization between the DTw and physical system [231].

- Part 1 - Overview and general principles [137]: provides an overview of the general principles of DTw, as well as definitions, requirements, and development guidance.
- Part 2 - Reference architecture [232]: provides an architecture reference model for a manufacturing DTw framework.
- Part 3 - Digital representation of manufacturing elements [233]: helps to identify the physical elements that need to be mapped to the digital model.
- Part 4 - Information exchange [234]: establishes the requirements for proper synchronization and exchange of data throughout the DTw framework.
- Part 5 (Currently in draft version under development) - Digital thread for digital twin [235]: describes how the Digital Thread facilitates the creation, connectivity, management, and maintenance of manufacturing Digital Twins throughout the product lifecycle by outlining principles, demonstrating methodologies, and providing case studies.

Figure 4.4 illustrates the Digital Twin framework derived from ISO 23247 Part 2 [232], delineated into four distinct domains.

The first layer pertains to the Observable Manufacturing Elements (OMEs) domain, encompassing devices, sensors, machines, materials, products, processes, and facilities requiring monitoring and control.

The second layer encapsulates the Data Collection and Device Control Entities (DCDCE), entrusted with overseeing sensor data and managing actuated devices within the OME domain. Additionally, this domain facilitates synchronization between OME entities and Digital Twin entities.

The DTw domain (third layer) comprises diverse system entities providing access to manufacturing services like simulation, provisioning, management, monitoring, analysis, and optimization. This domain serves as the nucleus of the DTw framework for manufacturing, emphasizing the interaction and integration capabilities of DTw entities for system interoperability.

Lastly, the fourth layer corresponds to the DTw user domain, housing entities seeking to leverage DTw services. These entities could range from individuals and companies to other systems.

Furthermore, a cross-system entity may span across domains, delivering essential functionalities such as information exchange, data assurance, and security support. This strategic placement ensures seamless collaboration and interoperability across the entire DTw framework.

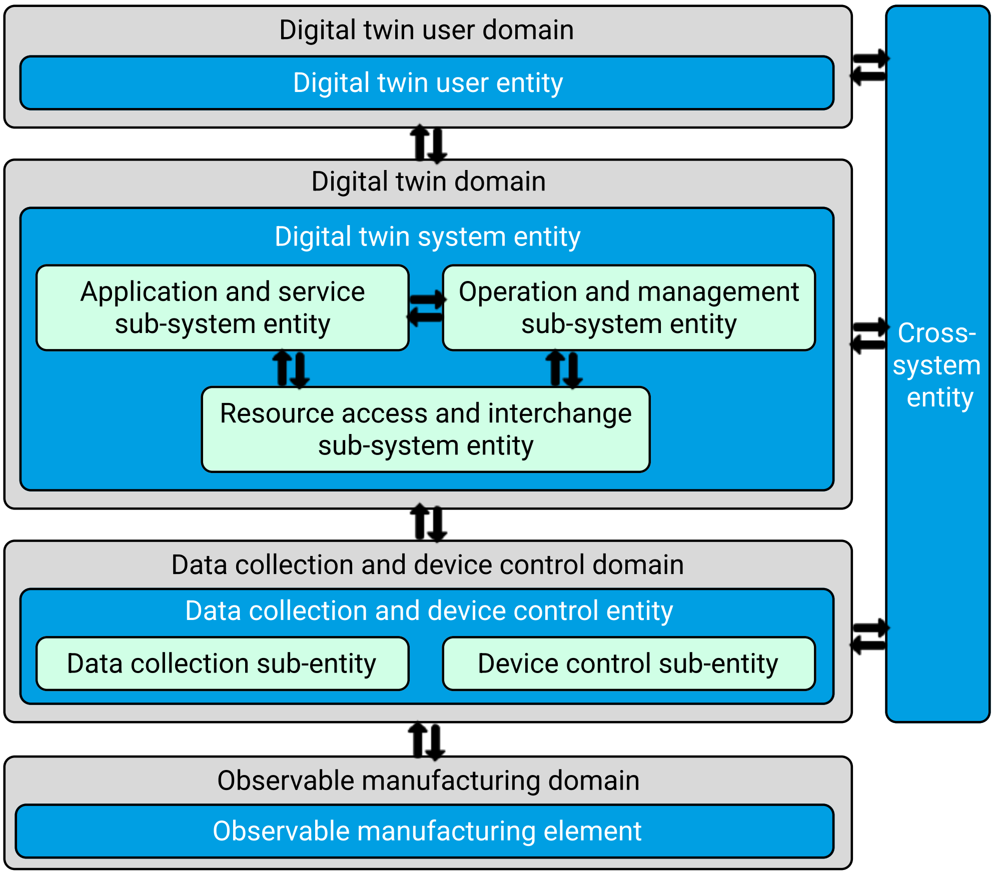


Figure 4.4: DTw framework for manufacturing from ISO 23247 Part 2 [232].

4.1.2.6 Research on ISO 23247 framework

The ISO 23247 framework is starting to gain attention within the research community, marking a shift from its initially underexplored status. Notably, the NIST has leveraged this framework as a template for implementing DTw in its SMS Testbed project, unveiling three distinct use cases: machine status and condition monitoring, production scheduling and routing, and virtual commissioning [236].

Kim et al. [237] introduce a comprehensive DTw implementation for Wire + Arc Additive Manufacturing (WAAM) using ISO 23247. This framework tackles integration and interoperability challenges, empowering manufacturers for real-time decision-making and control. The work illustrates an application scenario with machine learning-based anomaly detection in WAAM within this architecture.

Cabral et al. [238] present an implementation of DTw based on the ISO 23247 framework, where the focus is on real-time monitoring and 3D simulation in a CNC Haas MiniMill. Leveraging MQTT and MTConnect protocols, the system efficiently transfers machining process and machine status data to enable both on-the-edge monitoring through NodeRed and cloud-based 3D simulation using React js, Three js, and IBM Watson. This integrated solution highlights the feasibility of applying this approach to diverse machines and manufacturing scenarios.

The study carried out by Wallner et al. [239] explores the implementation of DTw in flexible manufacturing cells, leveraging ISO standards, including ISO 21597, ITU-T Y.3090, and ISO 23247. The goal is to enhance the efficiency of DTw application setup and maintenance by identifying key features, parameters, and assets. The focus encompasses manufacturing elements such as machine tools, robots, and peripheral devices, alongside information systems like CAM, PLM, and MES. To streamline lifecycle changes, the paper proposes linking to a lifecycle meta-layer, simplifying design, deployment, and updates of DTw applications, ultimately reducing maintenance efforts.

Recently, Shtofenmakher et al. [240] adapted the ISO 23247 standard from manufacturing to the aerospace sector. The focus on collision avoidance in low Earth orbit (LEO) demonstrates the feasibility of applying existing DTw standards to aerospace challenges, providing a standardized framework for this crucial process. The study extends its scope to space-based detection of sub-10-cm-class orbital debris, highlighting the framework's versatility for diverse aerospace applications.

Ongoing efforts to refine the ISO 23247 framework face challenges in consistent implementation, emphasizing the need for standardized practices to elevate DTw into valuable tools for optimizing production processes and operations [231, 241].

4.2 Research on DTw in AM processes

To investigate the current state of research on DTw technology in AM, a systematic search was performed using the Scopus database. Using key terms such as "additive manufacturing," "3D printing," and "rapid prototyping," combined with "digital twin," a significant corpus of 568 documents was identified. This reflects a remarkable interest in the application of DTw technologies to AM processes, underscoring their potential to transform manufacturing paradigms in line with Industry 4.0 principles.

The annual trend in research publications, as shown in Figure 4.5, reveals an exponential growth starting from 2016. By 2024, the number of publications reached 182, representing a fourfold increase compared to 2020. This rapid expansion shows the rising global recognition of DTw as a cornerstone technology in AM. The ability of DTw to enable real-time process monitoring, predictive maintenance, and seamless integration across manufacturing workflows has fueled this surge. The notable spike in recent years aligns with the increasing adoption of data-driven and digital-first approaches within the advanced manufacturing sectors, further solidifying DTw as a critical enabler of smarter AM systems.

A geographical analysis, depicted in Figure 4.6(a), reveals that the United States leads this research domain with 137 publications, nearly double that of Germany, which ranks second. This

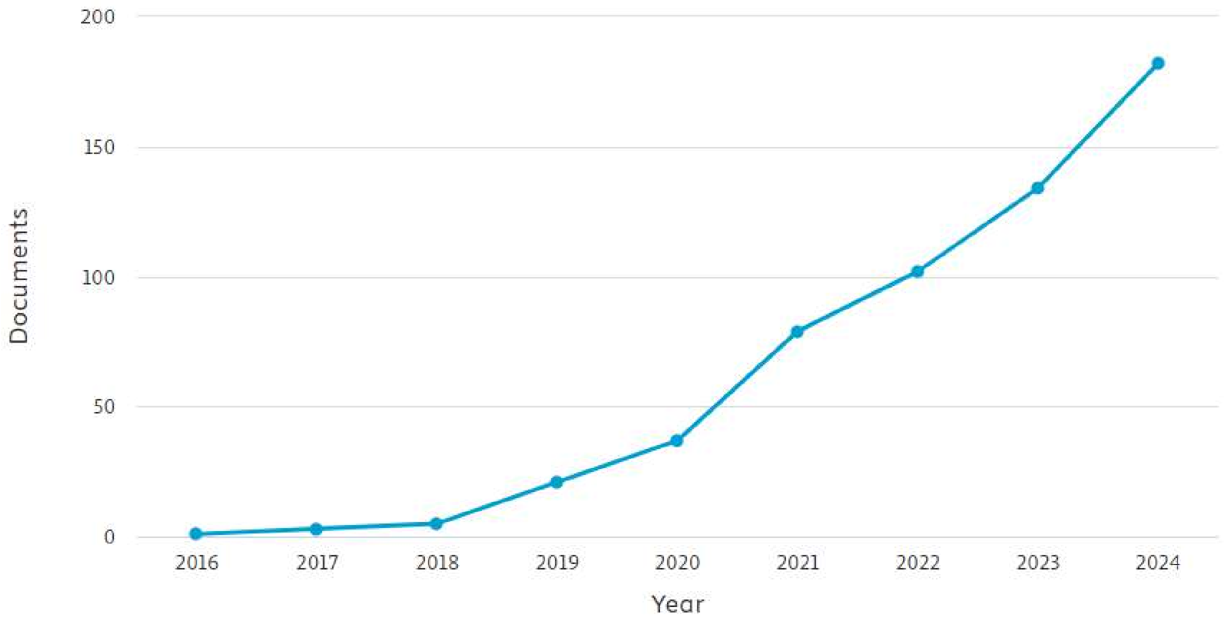


Figure 4.5: Publications by year on Digital Twin in AM using the query TITLE-ABS-KEY ((“additive manufacturing” OR “3D printing” OR “rapid prototyping”) AND (“Digital Twin”)).

dominance highlights the strong emphasis placed by U.S. institutions and industries on advancing DTw applications in AM. Germany’s significant contribution reflects its ongoing commitment to Industry 4.0, where DTw plays a pivotal role in streamlining manufacturing advancements. The global distribution of research reinforces the universal relevance of DTw technologies, showing how both advanced and emerging economies are leveraging them to address key challenges in AM processes.

When examining contributions at the institutional level, as shown in Figure 4.6(b), the NIST stands out as the most prolific organization. NIST’s role underscores the importance of public research institutions in establishing foundational methodologies and standards for DTw applications. Siemens AG, positioned as the sixth-leading contributor, represents the significant involvement of the industrial sector. Siemens’ contributions not only demonstrate the practical applications of DTw technologies but also highlight the industry’s role in driving innovation and bridging the gap between research and real-world implementation. This blend of academic, governmental, and industrial efforts signals the collaborative nature of DTw research, essential for addressing the complex challenges of AM.

The development DTw in AM have become a focal point of contemporary research. Professor Debroy’s team has pioneered the development of this subject by conducting a series of research studies aimed at reducing or replacing the time-consuming and expensive trial-and-error experiments commonly used to predict the process parameters that affect the structure and mechanical properties of printed metal parts [242, 243]. On the basis of these studies, Mukherjee et al.

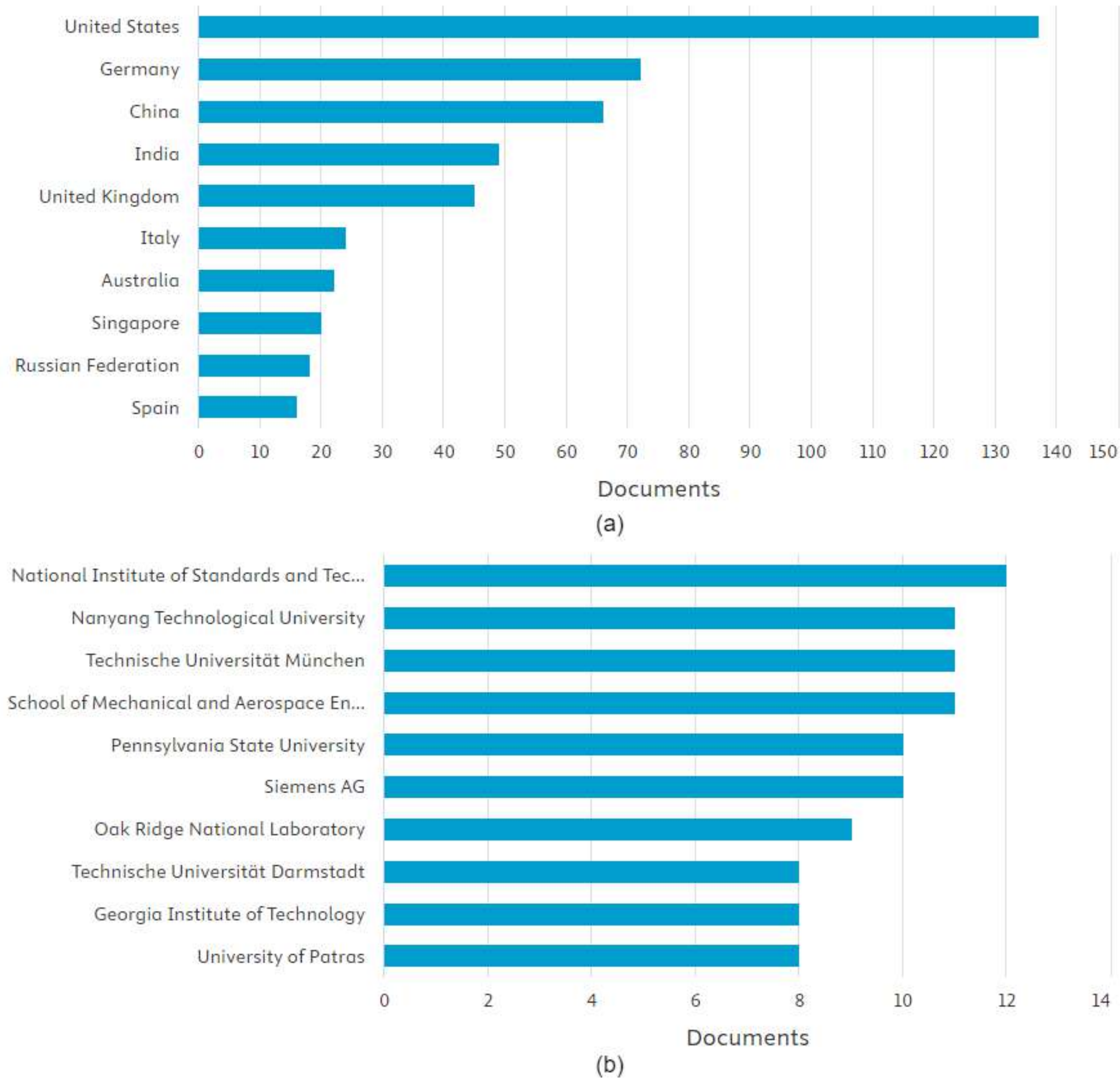


Figure 4.6: Publications by year on Digital Twin in AM using the query TITLE-ABS-KEY ((“additive manufacturing” OR “3D printing” OR “rapid prototyping”) AND (“Digital Twin”)).

[244] applied and tested the building blocks of the DTw proposed in previous work to efficiently estimate cooling rates, solidification parameters, secondary dendrite arm spacing, velocity distributions, and micro-hardness in powder bed fusion and direct energy deposition processes. They argue that the components of a DTw for AM should include mechanistic and statistical models, machine learning, Big Data analytics, and sensing and control [244, 71].

After conducting a thorough literature review, examining review papers such as those by Zhang et al. [245], Bartsch et al. [246], and Gunasegaram et al. [247], it becomes evident that previous research in the realm of DTw for AM has predominantly concentrated on predictive analysis [242, 243, 244], in-process monitoring [248, 70, 249], process control [250, 251, 237], and parameter optimization [249, 252, 253]. Recently, Shen and Li [254] have presented a comprehensive analysis of DT applications in AM based on a literature review, identifying advancements, discussing cross-domain applications, and proposing directions for improvement and future research.

Cai et al. [255] presented a methodology based on an augmented reality-enabled DTw approach for toolpath planning and simulation using multiple manipulator robots in an FDM process. They focused on the communication and synchronization of the robotic arm system with its corresponding DTw. On the other hand, the concept of virtual part inspection for additive manufacturing is proposed by Krückemeier and Anderl [256], who have used a DTw approach to predict as-built part properties based on data recovered from the product development and manufacturing process.

Mandolla et al. [257] developed a DTw of metal additive manufacturing to securely manage, organize and track product-related data throughout the supply chain in the aircraft industry based on Blockchain technology. Similarly, Guo et al. [258] combined DTw and Blockchain technologies with additive manufacturing processes within a framework for customized and personalized production in the context of Industry 4.0.

Guo et al. [259] propose a cloud-edge collaboration architecture for 3D printers in cloud manufacturing. Using DTw technology, they address challenges such as network pressure and latency. The system features time-sensitive services at the edge, ensuring reliable local extension of cloud services. Real-time control and monitoring for FDM process are achieved through a defined DTw information model. The study provides an effective solution, demonstrated through an implemented application case, offering insights for cloudifying various manufacturing equipment in cloud manufacturing environments.

Osho et al. [260] proposed a conceptual framework for creating a general-purpose, modular DTw consisting of four phases (4Rs): Representation, Replication, Reality, and Relational. They emphasized the implementation of the representation phase with a use case where they carried out experiments of monitoring extruder temperature and machine axes positions under variant conditions using an FDM 3D printer. Meanwhile, Yu and Xu [261] introduced a DTw framework to realize augmented reality-assisted cloud additive manufacturing that allows multi-stakeholders to work and cooperate in customizing complex products.

As previously mentioned in Section 4.1.2.6, Kim et al. [237] introduce a comprehensive implementation of DTw for Wire + Arc AM using ISO 23247. This framework addresses integration and interoperability challenges, empowering manufacturers for real-time decision-making and control. The work illustrates an application scenario with machine learning-based anomaly detection in WAAM within this architecture.

Moreover, Liu et al. [262] proposed a DTw-enabled collaborative data management approach for metal additive manufacturing systems based on a cloud DTw that communicates with distributed edge Digital Twins in different product lifecycle stages. The authors carried out a use case for layer defect analysis through a deep learning model within the Manuela project platform. They concluded that the proposed approach showed great potential in reducing development times and costs, and improving product quality and production efficiency.

Tariq et al. [263] offer insights into the future prospects of integrating a spectrum of advanced technologies, including automation, AI, IoT, additive and subtractive manufacturing, hybrid manufacturing, and real-time feedback through sensors and DTw, aiming to optimize and streamline manufacturing operations in a digital factory.

Jyeniskhan et al. [264] propose an integrated DTw system for AM that utilizes machine learning models, achieving a remarkable 92% Average Precision for defect detection. The system, incorporating Unity, OctoPrint, and Raspberry Pi, ensures real-time control and monitoring of the AM process. With a user-friendly Unity client interface, the framework demonstrates high efficiency in defect detection (91% for defected objects and 94% for non-defected). The study contributes significantly to enhancing AM quality and reliability through advanced DTw technology.

Castelló et al. [265] tackle challenges in simulating material extrusion for large-format AM. They propose a DTw for pellet extrusion, emphasizing its role in preventing part distortion due to warpage and residual stresses. The study's application to large-format AM pellet extrusion demonstrates effective predictions of elastic properties, despite limitations in accuracy in the plastic region. The research contributes insights into advanced material modeling for composite parts in AM, showcasing its applicability to real-world applications, such as the manufacturing of a wind turbine blade mold.

Phua et al. [266] introduce a groundbreaking framework for enhancing the layering process in metal AM. The proposed Smart Recoating approach leverages Bayesian optimization and digital methodologies to dynamically control powder spreading in a PBF process based on a DTw. Their innovative DTw control system, demonstrated within a comprehensive simulation framework, showcases its potential to mitigate process variation and ensure consistent print quality across layers in metal AM processes.

Rachmawati et al. [267] present an innovative approach for early failure detection in FDM 3D printers, addressing material waste concerns. Their DTw-based solution integrates AI technology, utilizing a Lightweight Convolutional Neural Network for sensor data-driven fault diagnosis. The proposed DTw technology enhances fault detection by creating a virtual representation of the physical object. Simulation results demonstrate the effectiveness of the solution achieving an F1-Score of 0.9981 and establishing a foundation for intelligent and autonomous factories through virtual condition monitoring of 3D printer abnormalities.

Reisch et al. [268] introduce a solution for achieving first-time-right printing in Wire Arc AM through a smart manufacturing system. This system leverages a DTw to predict the welding torch's future position, analyze its spatial context, and adapt process parameters to compensate for previously created defects. The proposed approach ensures fault-tolerant manufacturing, aiming for a first-time-right process and minimizing production scrap due to insufficient part quality.

Chen et al. [269] propose a multisensor fusion-based DTw for in-situ quality monitoring and defect correction in a robotic laser-directed energy deposition process. The system integrates multiple sensors, synchronizing features within the part's 3D volume to predict location-specific quality. This allows on-the-fly identification of regions requiring material addition or removal, enabling defect correction through robot toolpaths and auto-tuned process parameters. Multi-sensor fusion enhances understanding of process physics, facilitating self-adaptation in AM for increased efficiency and cleaner production.

Putra et al. [270] present a novel federated learning-enabled DTw architecture for smart additive manufacturing. Overcoming centralization issues, their model efficiently updates fault detection through distributed learning, showcasing an 8% accuracy boost. The proposal includes a CNN-based model for effective sensory data learning and a robust DTw platform for seamless monitoring and control. Experimental results affirm low overall latency (1026.16 ms) from the physical 3D printer to the DTw platform, highlighting its potential for enhancing fault detection in smart additive manufacturing.

Sampedro et al. [271] introduce an advanced DTw system, leveraging the powerful 3D-AmplifAI algorithm for real-time fault monitoring in AM 3D printers. This innovative approach, operating in both the physical and virtual realms, ensures continuous monitoring of temperature values to detect and prevent potential printer damage. The ensemble 3D-AmplifAI algorithm, combining multiple machine learning models, outperforms state-of-the-art methods in accuracy, precision, recall, and F1-score. This system offers a streamlined solution to resource-intensive testing challenges and enhances the reliability of 3D printing processes.

The integration of DTw in AM not only facilitate real-time monitoring and control of processes but also promote early defect detection, enabling precise adjustments and optimizations. Their ability to bridge the virtual and physical worlds opens new frontiers in improving quality, operational efficiency, and sustainability in AM in the context of Industry 4.0.

Table 4.3 provides a synthesis of the analyzed references, highlighting the purpose of each study, the related technologies employed, and whether full integration with the DTh is achieved. This summary emphasizes the diverse applications of DTw in AM, showcasing the breadth of technological innovations and their varying levels of alignment with the principles of a fully interconnected manufacturing lifecycle.

Table 4.3: Overview of DTw applications in AM

Reference	Purpose of DTw Usage	Related Technologies	Full integration with DTh
[255]	Toolpath planning and simulation for FDM robotic arms	Augmented Reality, Robotic Systems	Partial
[256]	Virtual part inspection to predict as-built properties	Data analysis from development and manufacturing stages	Partial
[257]	Managing product data across supply chains in aircraft industry	Blockchain Technology	Partial
[258]	Framework for customized production with AM	Blockchain Technology, AM-specific frameworks	Partial
[259]	Cloud-edge collaboration for 3D printers	Cloud Manufacturing, Edge Computing	Partial
[260]	Modular DTw framework for FDM monitoring	FDM 3D Printing, Modular Architecture	No
[261]	Augmented reality-assisted cloud AM for customization	Augmented Reality, Cloud Computing	Partial
[237]	DTw for Wire + Arc AM, real-time decision-making	ISO 23247, Machine Learning	Partial
[262]	Collaborative data management with layer defect analysis	Cloud Computing, Deep Learning	Partial
[263]	Integration of advanced technologies for smart factories	AI, IoT, Hybrid Manufacturing	Partial
[265]	Simulating material extrusion for large-format AM	Material Extrusion, Residual Stress Modeling	No
[266]	Dynamic powder spreading control in PBF	Bayesian Optimization, PBF Process	Partial
[268]	First-time-right printing in WAAM	Smart Manufacturing Systems, WAAM	Partial
[269]	In-situ quality monitoring in laser deposition	Multisensor Fusion, Robot Toolpaths	Partial

Chapter 5

STEP-NC as a Method for Integrating Contextualized Data in a Digital AM Ecosystem

5.0.1 Overview of the STEP and STEP-NC standards

In the late 1980s, a global initiative led to the establishment of ISO 10303 [272], known as STEP (STandard for the Exchange of Product model data), aimed at creating a universal language for representing product information throughout its lifecycle [273]. STEP's system-agnostic design allows for seamless information exchange between diverse computational environments, facilitating collaborative sharing among multiple users. Its ongoing vision is to promote standardized product data exchange across the entire CAx chain for widespread industry adoption [274].

The STEP standards series is structured into separate documents called "Parts", each published independently [272]. These Parts belong to distinct categories such as Description Methods, Implementation Methods, Application Protocols, Integrated Resources, Application Interpreted Constructs, Application Modules, Application Domain Models, Core Models, Conformance Testing Methodology and Framework, and Abstract Test Suites. Moreover, these categories can be further classified into environment, integrated data models, and top-level Parts. Each Part is designated a numerical identifier, ensuring Parts of the same type fall within a specific number range. With approximately 700 Parts, the STEP standard firmly establishes itself as a prominent technology within the ISO standard. Table 5.1 provides a breakdown of its organizational structure.

Table 5.1: Organization of Parts within the STEP standards series

Sections	Categories	Part number
Infrastructure	Overview and fundamental principles	Part 1
	Description methods	Parts 1X
	Implementation Methods	Parts 2X
	Conformance testing methodology and framework	Parts 3X
Integrated information models	Integrated resources	Parts 4X, 5X and 1xx
	Application interpreted constructs	Parts 5XX
	Application modules	Parts 4XX and 1XXX
	Core models	Parts 4XXX
	Application domain models	Parts 4XXX
Top-level Parts	Application protocols	Parts 2XX
	Abstract test suites	Parts 3XX

5.0.1.1 Description method EXPRESS

To shed light on some key Parts of STEP, Part 11 (ISO 10303-11) [275], describes the EXPRESS language, a precise and concise Description Method designed specifically for defining data models within the STEP standard. Adopting an object-oriented modeling paradigm reminiscent of programming languages such as C++ or Java, EXPRESS streamlines the creation of logical data models through entities that represent pertinent data objects. These entities are defined by their attributes, each with a specific domain encompassing either simple data types or other entity types. Furthermore, EXPRESS elucidates the intricate relationships between entities, spanning inheritance, composition, or aggregation. However, it's essential to note that EXPRESS itself is not an executable programming language; rather, it functions as a descriptive tool harnessing object-oriented principles to craft comprehensive data schemas capable of encapsulating diverse product information. An example EXPRESS schema is described in the code below:

```
SCHEMA example;

TYPE date = ARRAY [1:3] OF INTEGER;
END_TYPE;

TYPE hairType = ENUMERATION OF (blonde, brown,black, red, white);
END_TYPE;

ENTITY person
```

```
    ABSTRACT SUPERTYPE OF (ONEOF(female, male));
    firstName : STRING;
    lastName : STRING;
    nickname : OPTIONAL STRING;
    birthDate : date;
    children : SET [0:?] OF person;
    hair : hairType;
    DERIVE
        age : INTEGER := years(birthDate);
    INVERSE
        parents : SET [0:2] OF person FOR children;
END_ENTITY;

ENTITY female SUBTYPE OF (person);
    INVERSE
        husband : SET [0:1] OF male FOR wife;
END_ENTITY;

ENTITY male SUBTYPE OF (person);
    wife : OPTIONAL female;
END_ENTITY;

FUNCTION years(past : date) : INTEGER;
(* This function calculates the number of years
 between the past date and the current date *)
END_FUNCTION;

END_SCHEMA;
```

Additionally, EXPRESS-G (also included in ISO 10303-11 [275]) provides a graphical representation of EXPRESS schemas, providing visual clarity and aiding in understanding complex data structures. The graphical representation in EXPRESS-G of the schema above illustrates Figures 5.1, with attributes like name and date of birth, can have children and be part of relationships like marriage.

5.0.1.2 Implementation methods

ISO 10303 provides three Implementation Methods for representing and storing STEP entity instances in either physical files or databases. Part 21 (ISO 10303-21 [276]) and Part 28 (ISO 10303-28 [277]) enable the recording of entity instances in physical files using clear text

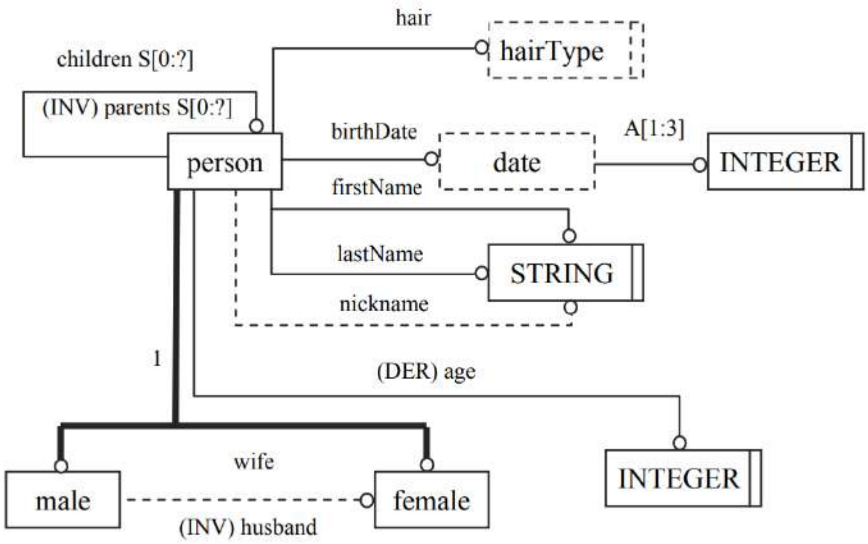


Figure 5.1: Example EXPRESS-G diagram [274]

encoding and XML (Extensible Markup Language)-based format, respectively. Meanwhile, Part 22 (ISO 10303-22 [278]), known as SDAI (STEP Data Access Interface), provides a language-independent API (Application Programming Interface) for handling STEP data to store them in databases. Part 28 facilitates the transfer of STEP data via XML on the web, while SDAI empowers the implementation of EXPRESS models into virtually any programming language. Notably, specific standards based on SDAI API have been established for various programming languages, such as the C++ language binding in Part 23 (ISO 10303-23 [279]), the C language binding in Part 24 (ISO 10303-24 [280]), and the Java programming language binding in Part 27 (ISO 10303-27 [281]).

5.0.1.3 Part 21 - Clear text encoding of exchange structure

Part 21, known as "clear text encoding of exchange structure", stands out as the most widely used implementation method. This method entails the use of a sequential text file, often referred to as "Part 21 file", consisting of a header section and up to four optional sections: anchor, reference, data, and signature sections. The header section contains essential information such as file description, name, and schema, marked by the tokens "HEADER;" and "ENDSEC;". The anchor section, if included, defines external names for instances, marked by "ANCHOR;" and "ENDSEC;" The reference section, also optional, associates occurrence names with resources, denoted by "REFERENCE;" and "ENDSEC;" tokens. The data sections contain entity instances governed by the schema in the header, following a strict syntax that begins with "DATA;" and ends with "ENDSEC;". Each entity is identified by a unique ID, followed by its instance name and attribute values. Lastly, signature sections may be included to indicate verified content, starting with "SIGNATURE;" and concluding with "ENDSEC;". An example Part 21 file is presented in Figure 5.2.

```
ISO-10303-21;
HEADER;
/* Generated by software containing ST-Developer
 * from STEP Tools, Inc. (www.steptools.com)
 */

FILE_DESCRIPTION(
/* description */ ('ARM_SCHEMA: ap238_arm_schema'),
/* implementation_level */ '4;1');

FILE_NAME(
/* name */ 'test_part_standard_STEP-NC_ok',
/* time_stamp */ '2017-10-11T14:59:02-04:00',
/* author */ ('STEP-NC Maker 3.0'),
/* organization */ (''),
/* preprocessor_version */ 'ST-DEVELOPER v17',
/* originating_system */ 'Various',
/* authorisation */ '');

FILE_SCHEMA (('INTEGRATED_CNC_SCHEMA'));
ENDSEC;

DATA;
#10=PRODUCT_DEFINITION('','',#14,#16);
#11=MACHINING_PROJECT_WORKPIECE_RELATIONSHIP('','','',#10,#20);
#12=PROCESS_PRODUCT_ASSOCIATION('','',#10,#13);
#13=PRODUCT_DEFINITION_PROCESS('machining','',#18,'');
#14=PRODUCT_DEFINITION_FORMATION('','',#15);
#15=MACHINING_PROJECT('test_part_standard_STEP-NC_ok','',$,(#17));
#16=PRODUCT_DEFINITION_CONTEXT('CNC Machining',$,'manufacturing');
#17=PRODUCT_CONTEXT('CNC Machining',$,'manufacturing');

...

ENDSEC;
END-ISO-10303-21;
```

Figure 5.2: Part 21 file example

5.0.1.4 Application Protocols (APs)

In tandem with Description Methods like EXPRESS for data modeling and Implementation Methods such as Part 21 for defining data exchange structures, Application Protocols (APs) are essential elements in the realization of STEP standards. These APs (Parts 2XX in ISO 10303) describe the entities and their relationships to model data for a specific industrial application domain (e.g., design, machining, inspection, etc.). As APs can become extensive, containing hundreds or thousands of entities, modularization strategies were adopted through Integrated Resources (Parts 4X, 5X and 1XX), Application Modules (4XX and 1XXX), Application Interpreted Constructs (5XX), Core Models (Parts 4XXX), and Units of Functionality. Presently, STEP boasts 23 well-established APs. Some of the commonly used APs in commercial CAD/CAM systems include:

- STEP 203 (ISO 10303-203 [128]) is tailored for mechanical component design and 3D configuration control. Initially lacking layer and color capabilities, the second edition introduced enhancements compatible with AP214.
- STEP 214 (ISO 10303-214 [129]) is designed for automotive mechanical design, featuring layer and color management, GD&T (Geometric Dimensioning and Tolerance), 3D construction history, kinematic structures, and more.
- STEP 242 (ISO 10303-242 [130]) focuses on managed model-based 3D engineering, merging features from AP214 and AP203. It includes functionalities like 3D PMI (Product & Manufacturing Information), 3D composite design, 3D electrical harness, 3D, kinematics assembly, shape quality, 3D features for machining and additive manufacturing, and explicit/parametric 3D shape presentation through 3D tessellated geometry and 3D curved triangles. This AP offers significant potential for representing AM data including feature-based 3D complex geometries, curved triangle mesh, multi-material parts, and process parameters. An overview of the structure of the ISO 10303 AP242 is depicted in Figure **??**.

Additional APs of interest to highlight are AP224 for feature-based process planning [282], AP219 dedicated to dimensional inspection information exchange [283], AP240 focusing on macro process planning [284], and AP238, which deals with application interpreted model for computerized numerical controllers [133].

5.0.1.5 STEP modeling types

The construction of APs within the STEP ecosystem is based on three key models: AAM (Application Activity Model), ARM (Application Reference Model), and AIM (Application Interpreted Model). The AAM delineates application activities and data flows using the IDEF0

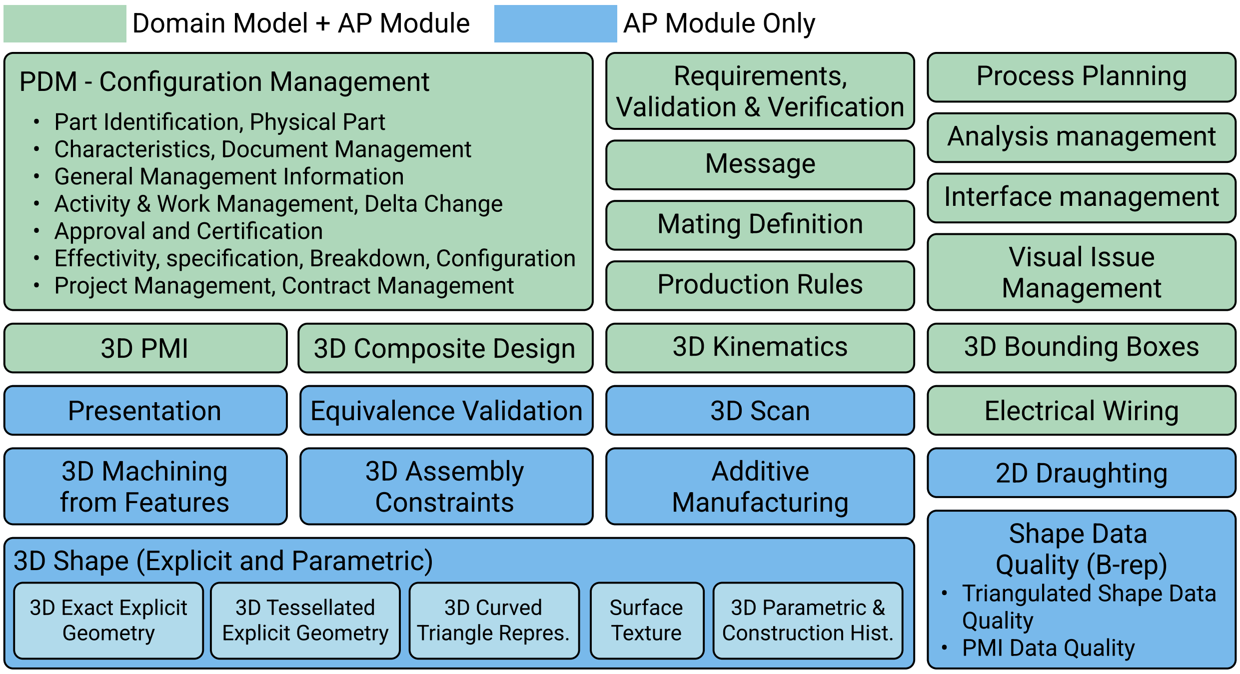


Figure 5.3: Overview of the ISO 10303 AP242 [127]

method, providing a high-level overview that undergoes refinement to generate the ARM. In contrast, the ARM represents application-specific data requirements in terminology understandable to practitioners, typically developed through workshops with domain experts [274]. Finally, the AIM encodes the ARM into an EXPRESS model using STEP integrated resources. Furthermore, Abstract Test Suites, specified in Parts 3XX, consist of predefined test cases designed to assess APs implementations' adherence to STEP standards, covering various aspects such as data structure, semantics, and interoperability. Meanwhile, the Conformance Testing Framework, outlined in Parts 3X, complements the Parts 3XX providing a systematic approach to verify compliance with ISO 10303. Together, they facilitate the development of interoperable and standards-compliant STEP software solutions.

5.0.2 STEP-NC

While STEP has been developed to address the challenges of product data integration across CAD/CAPP/CAM systems, the new standard STEP-NC is conceived with the purpose of extending this integration to the realm of CNC machine controllers, aiming to replace the entrenched G-code. Unlike traditional G-code, which often lacks semantic richness and is highly machine-specific, STEP-NC offers a standardized approach to describing manufacturing processes, leveraging the rich data model of STEP to provide comprehensive product context information for CNC machines. Both ISO 14649 and ISO 10303-238 target micro-level process planning, aiming to replace traditional G-code in NC machine tool programming, while ISO 10303-240 [284] addresses macro-level process planning information. Xu et al. [285] present a comparison between an ISO 14649 (ARM) and ISO 10303-238 (AIM) model, which is detailed in Table 5.2. Kramer et al. [286] concluded that both ISO 14694 and ISO 10303-238 (AP 238) are viable for implementing STEP-NC to control machining centers effectively. AP 238 accurately represents ISO 14649 information and enables real-time interpretation of STEP-NC data. However, building a STEP-NC interpreter, especially for AP 238, is challenging. The interpretation time increases linearly with file size for both standards, but interpreting AP 238 data takes significantly longer than ISO 14649 data using available software tools.

Table 5.2: Comparisons between an ISO 14649 (ARM) and ISO 10303-238 (AIM) model [285].

Comparison criteria	**ISO 14649 (ARM) model**	**ISO 10303–238 (AIM) model**
Storage needed	10 times less than AIM	10 times more than ARM
Programming	Easy	More complex
Human readable	Difficult	Almost impossible
Compatibilities with STEP	Partly compliant	Fully compliant
Data consistency	Original design information is abandoned	Original design information is preserved

The structure of ISO 14649, illustrated in Figure 5.4, comprises a series of Parts strategically designed to define manufacturing processes rather than focusing solely on machine tool motion. Part 1 [132] provides an overview and fundamental principles, while Part 10 [287] addresses general process data. Furthermore, Parts 11 through 14 [288, 289, 290, 291] delve into process data for specific machining operations such as milling, turning, wire-EDM (Electrical Discharge Machining), and sink-EDM, while Part 111 [292] and 121 [293] detail tool data for milling and turning, respectively. Of particular note is Part 17 [294], introduced in 2020, which specifically focuses on process data for AM processes. However, the data model of Part 17 is still in its early stages and requires expansion to encompass entities describing process parameters associated with specific AM technologies.

5.1 Overview of the current STEP-NC data model for AM

The current STEP-NC data model in ISO 14649 Part 17 has already been mapped as an extension of the AP238 model to support AM process entities within its edition 3 (current edition of AP 238 since 2022) [133]. This edition also maintains harmonization with other ISO 10303 APs such as AP242, AP224, AP219, among others, through modularized integration with integrated resources and application models (as depicted in Figure 5.4). Currently, edition 3 has also

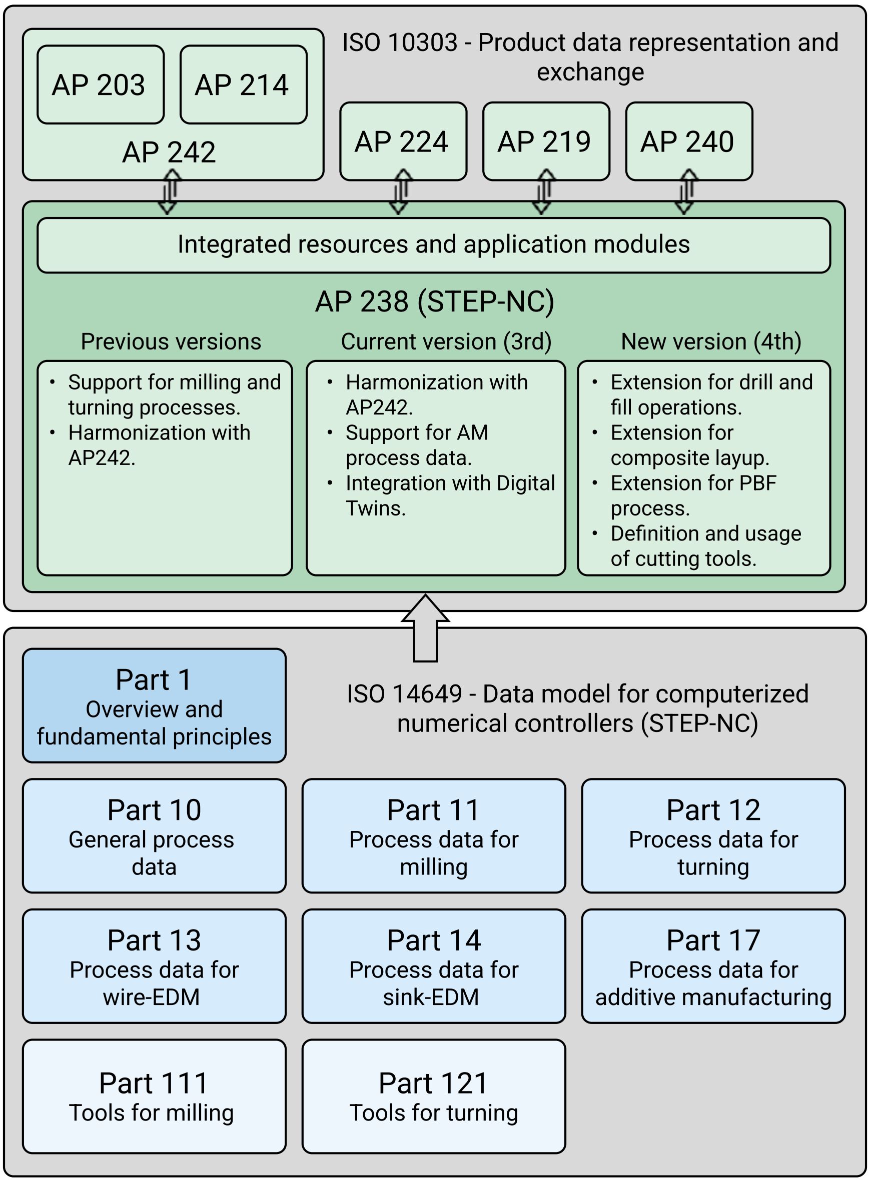


Figure 5.4: Overview of the structure of STEP-NC.

begun documenting entities that enable the integration of DTw data as a strategy for simulation, monitoring, and control of both processes and machines in manufacturing environments [295]. This vision aligns with the objective of the new ISO 23247 standard released in 2021 [137], also developed by the technical subcommittee SC 4 of ISO TC 184, which proposes a DTw framework for manufacturing.

A fourth edition of AP238 is currently under discussion in SC4 meetings, with industry participants such as STEP Tools Inc., Boeing, NIST, among others. This fourth edition aims to extend the data model of AP238 with new entities for four new capabilities [295]: drill and fill operations of fasteners in assemblies; layup of structures using composite tape; AM PBF process parameters; and, the definition and usage of cutting tools. The foundation of the data model supporting

PBF processes in such a fourth version of AP238 has been introduced in [296], which adds specifications for PBF thread operation, inter-layer relationship, scan strategy, and technology-related process parameters. STEP Tools Inc. has led practical demonstrations utilizing their proprietary Python library to showcase the integration of newly introduced AM model entities. This versatile Python library enables seamless creation and manipulation of STEP-NC programs [297]. Their comprehensive approach begins with CAD geometry importation, proceeds through intricate slicing procedures, and concludes with the generation of optimized toolpaths and parameters specifically for PBF processes [298].

Figure 5.5 presents an EXPRESS-G diagram delineating the core structure of the AP238 schema, featuring entities pertinent to AM processes highlighted in distinct colors. At the core of AP238 lies the `executable` entity, pivotal for orchestrating the execution of actions on a machine in a defined sequence. The `executable` entity encompasses four primary types of executable objects: `nc_function`, `program_structure`, `workingstep`, and `am_workplan`.

While `nc_function` entities describe switching operations or other non-interpolating machine functionality, such as singular events, the other types of executable objects define more comprehensive sequences of actions required for manufacturing processes. Specifically, the `program_structure` entity provides logical blocks essential for structuring STEP-NC programs, enabling sequential programming within a `workplan` or through adaptable, parallel, loop-based, or conditional sequences. Among these structures, the `workplan` stands out as the most critical type of `program_structure`, facilitating the grouping of workingstep sequences associated with an executable object.

The `workingstep` entity constitutes the fundamental component of a STEP-NC program, serving as the building block for manufacturing operations. It can be categorized into three primary types based on the nature of the manufacturing process: `machining_workingstep`, `turning_workingstep`, and `am_workingstep`. Within the `workingstep`, three crucial elements are encompassed: `workpiece`, `feature`, and `operation`. The `workpiece` is associated with the inherited property `to_be` from the `executable` entity, encapsulating information related to the 3D model of the part to be fabricated in its entirety. Conversely, the property `its_feature` delineates the shape, dimensions, and other attributes of the specific geometry (feature) to be created through the manufacturing operation (property `its_operation`) linked with the `workingstep`. Moreover, the operations can also contain an explicit and exact description of the toolpath if this is required by the NC controller.

For AM processes, an `am_workingstep`, represented by the green box in the Figure 5.5, comprises essentially an `am_workpiece` (pink box in Figure 5.5), an `am_feature` (orange box in Figure 5.5), and an `am_operation` (purple box in Figure 5.5). The geometry of an `am_feature` can be composed by connecting multiple features through an `am_compound_feature`, each defined as either an `am_simple_feature`, an `am_gradient_feature`, or an `am_heterogeneou`
The `am_simple_feature` describes a basic additive geometry with a uniform skin and core,

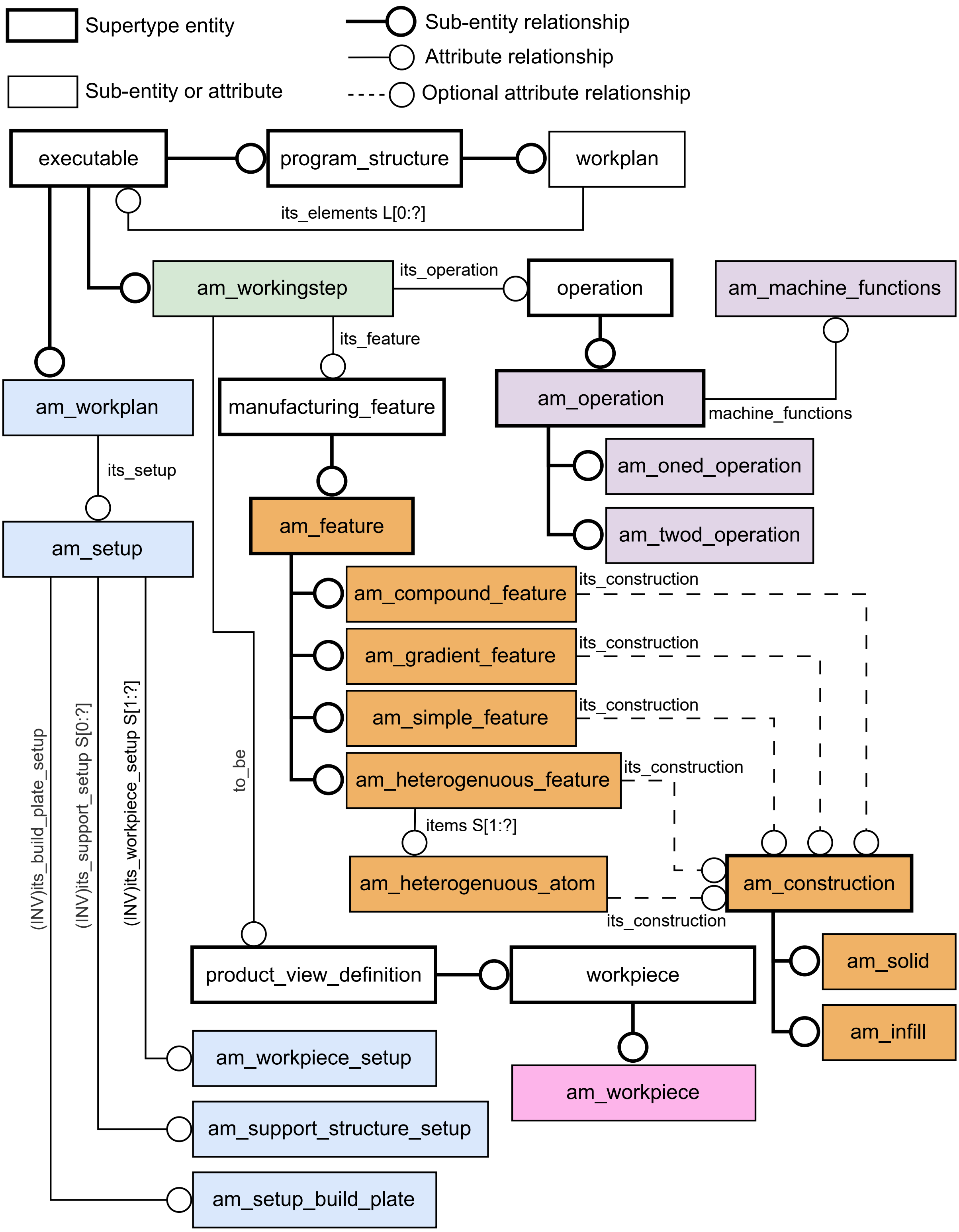


Figure 5.5: Current AM data entities mapped from ISO 14649 to the AP238 [295].

allowing for selection of a single color and material. Conversely, the `am_gradient_feature` permits the definition of color and material gradients within an `am_feature`, while the `am_heterogeneous` employs a freeform formula to depict atomic mixtures of multiple materials and colors within the same feature. Additionally, within each type of AM feature, there exists a property called its_construction, which establishes a connection to a construction strategy (am_construction entity). This strategy takes into account parameters such as density and construction direction, offering options for either a solid structure (am_solid entity) or one based on fill patterns (am_infill entity) like honeycomb, concentric, or rectilinear.

The operation entity serves as a supertype encompassing various types of manufacturing operations, including maching_operation, rapid_movement, touch_probing, and am_operation (illustrated by the purple box in Figure 5.5). An am_operation can further be categorized as either an am_oned_operation or an am_twod_operation. The former pertains to one-dimensional (1D) deposition processes, where material deposition occurs incrementally until the complete geometry is achieved. Conversely, the latter specifies two-dimensional (2D) operations on the geometry of each layer, determining layer thickness based on the normal direction. Moreover, an am_operation also interfaces with AM machine functions through the am_machine_functions entity and process parameters associated with a specific AM technology. Milaat et al. [296] have proposed a comprehensive set of entities to describe process parameters for PBF technology, which have been integrated into the fourth edition of AP238 [295]. Additionally, the am_workplan entity (blue box in Figure 5.5) emerges as an integral component of the core entities for AM within the current AP238 model. It functions as an executable object type capable of linking setup strategies for the workpiece, support structure, and build plate in AM processes.

Despite the existing core entities facilitating the description of AM processes within the AP238 structure, there remains a notable absence of entities to describe specific process parameters for other AM technologies (e.g. FDM, LMD). This represents an opportunity to propose models that enhance the current AP238 model for AM processes. Therefore, Section 5.2 calls for a thorough review of STEP-NC literature, with emphasis on AM processes.

5.2 Methodological Framework for the Literature Review

The literature review presented in this study was conducted utilizing the Scopus database, adhering to the methodological framework outlined in Figure 5.6. While the primary focus of this investigation lies in the advancement of STEP-NC with a particular emphasis on AM processes, an initial comprehensive search was conducted for research works pertaining to STEP-NC in a broader context. This initial search, aimed at gaining a broad perspective on the overall research landscape surrounding STEP-NC, involved querying terms such as “STEP-NC," “ISO 14649," “ISO 10303-238," and “AP238", as illustrated in flow (a) of Figure 5.6. This preliminary search yielded a corpus of 574 documents encompassing the broader domain of STEP-NC.

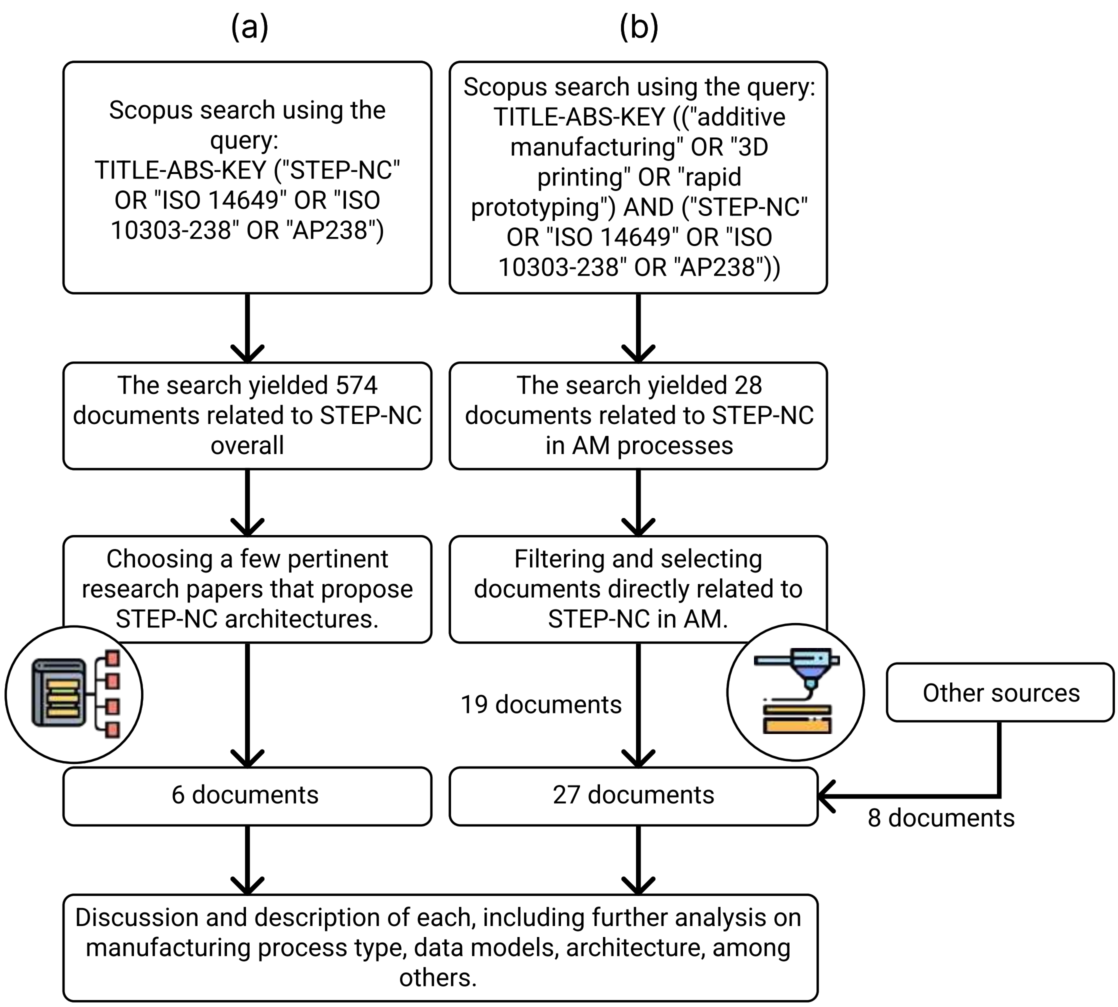


Figure 5.6: Literature review methodology.

As depicted in Figure 5.7(a), an analysis of the yearly publication trends related to STEP-NC from 2002 to 2024 reveals a significant spike in outputs between 2006 and 2010. This surge coincided with the establishment of data models for machining processes such as milling and turning within ISO 14649 and AP238 standards. Notably, this period saw a proliferation of STEP-NC implementations predominantly tailored to machining applications. However, recent years have witnessed a discernible downturn in publication activity, indicative of evolving research priorities and shifting emphases within the realm of manufacturing engineering. Nevertheless, from this extensive collection of 570 works, a carefully curated selection of 6 papers that delve deeply into the architectural aspects of STEP-NC has been chosen and will be discussed in a concise survey presented in Section 5.4.

On another front, a focused inquiry into the development of STEP-NC applied to AM processes was also conducted. Here, the query from the initial search was refined by incorporating key terms like “additive manufacturing," “3D printing," and “rapid prototyping", as depicted in flow (b) of Figure 5.6. This investigation yielded a total of 28 documents, meticulously scrutinized and distilled to a selection of 19 documents truly pertinent to STEP-NC research in AM. Subsequently, 8 additional documents were sourced from platforms like Google Scholar, bringing the final total to 27 documents.

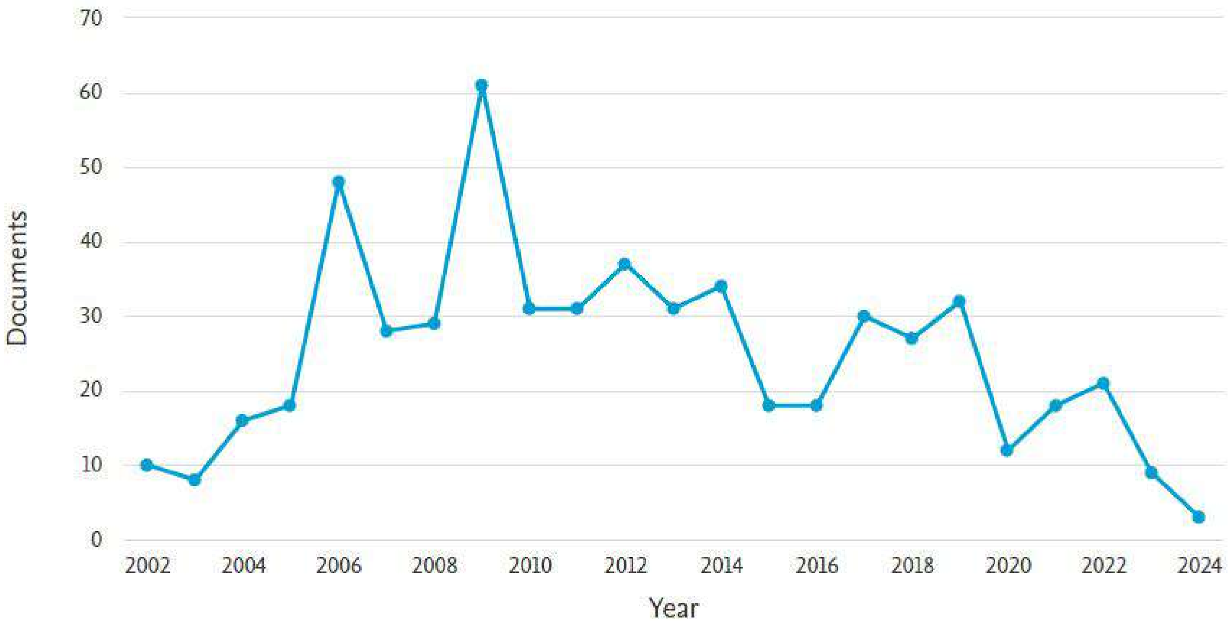
Figure 5.7(b) illustrates the number of scientific publications associated with STEP-NC in AM processes per year, revealing a recent uptick with a peak of five publications in 2019. Unlike broader research on STEP-NC, interest in the application of STEP-NC to AM processes has surged in recent years. This can be largely attributed to the rise of AM processes as an enabling technology of Industry 4.0 and its evolution in terms of materials, technology, and machine capabilities. Furthermore, its increasing adoption in industry through metal AM processes is opening new avenues in product development. Moreover, as previously mentioned, Part 17 of ISO 14649 was formalized in 2020, and ISO 10303 AP238 has also begun to incorporate entities to describe AM processes within the STEP-NC data model.

It's also significant to highlight that a substantial proportion—approximately 50%—of publications concerning STEP-NC in AM emanate from countries such as France, the United States, and Brazil (See Figure 5.8(a)). Notably, a select few institutions from these nations spearhead these impactful contributions (See Figure 5.8(b)).

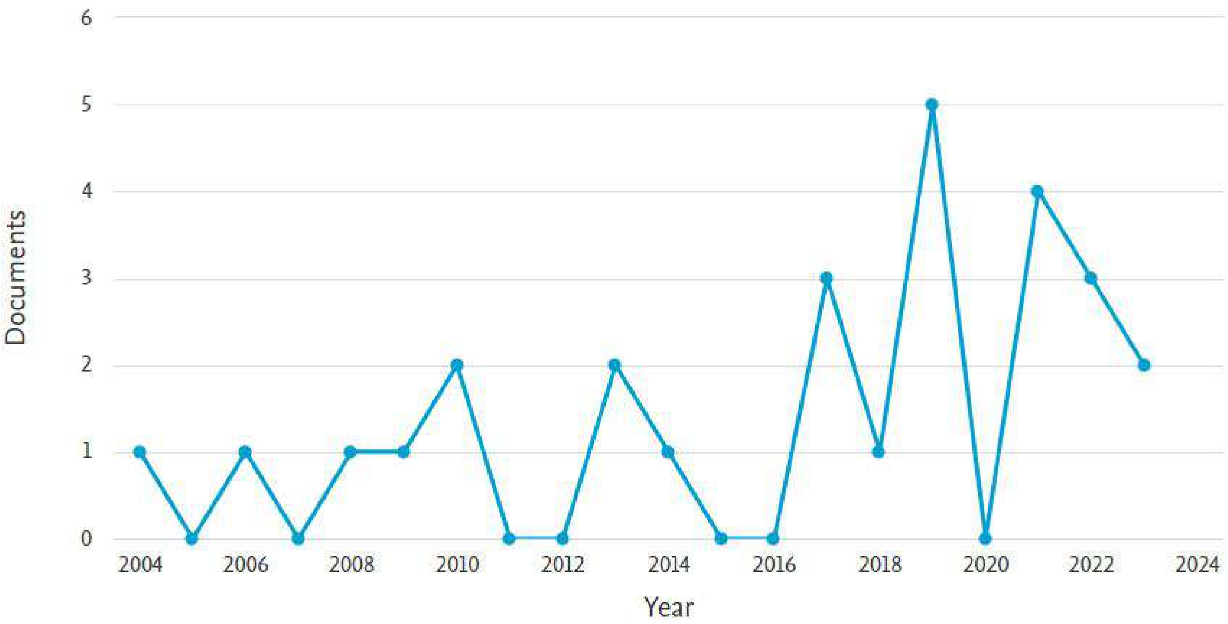
5.3 Research review on STEP-NC in AM processes

Since the 1990s, researchers have increasingly identified the STEP format as a promising standard for seamlessly integrating CAD information with AM processes. In 1994, Carleberg [299] suggests employing geometric data in STEP format coupled with process parameters for a solid free-form fabrication system. Gilman and Rock [300] describe an architecture and methodology to integrate CAD data using STEP and a solid free-form fabrication system. Kumar and Dutta [301] underscore the potential substitution of STL with STEP, specifically emphasizing the use of AP204 and resources outlined in Part 42 for layered manufacturing. Building on this concept, Dutta et al. [302] and Pratt et al. [303] advocate for the creation of a dedicated AP within the STEP standard, tailored to meet the specific needs of layered manufacturing. Meanwhile, a method of slicing and editing STEP-based models for rapid prototyping is proposed in [304].

While numerous researchers have recently acknowledged the potential of STEP [183, 186, 200, 305], particularly through APs like 203, 214, and 242, to encompass part geometry and process parameters for AM processes, there is a recognized need for a more comprehensive solution that extends to the CNC level, such as STEP-NC [186, 306, 305]. Examples showcasing the integration of CAD-CAM-Simulation-CNC facilitated by STEP-NC in accordance with ISO 10303 AP-238 are documented in [307]. The implementation challenges associated with STEP-NC in comparison to traditional G-code have hindered its widespread adoption as the industry standard. Despite this, the realm of research has experienced substantial advancements in the



(a)



(b)

Figure 5.7: Documents by year: (a) Publications on STEP-NC overall using the query TITLE-ABS-KEY ("STEP-NC" OR "ISO 14649" OR "ISO 10303-238" OR "AP238"); (b) Publications on STEP-NC in AM using the query TITLE-ABS-KEY (("additive manufacturing" OR "3D printing" OR "rapid prototyping") AND ("STEP-NC" OR "ISO 14649" OR "ISO 10303-238" OR "AP238")).

application of STEP-NC over the past two decades, particularly in the domains of machining [308, 74, 309, 310], turning [311, 312, 313], EDM [314, 315], process optimization and energy

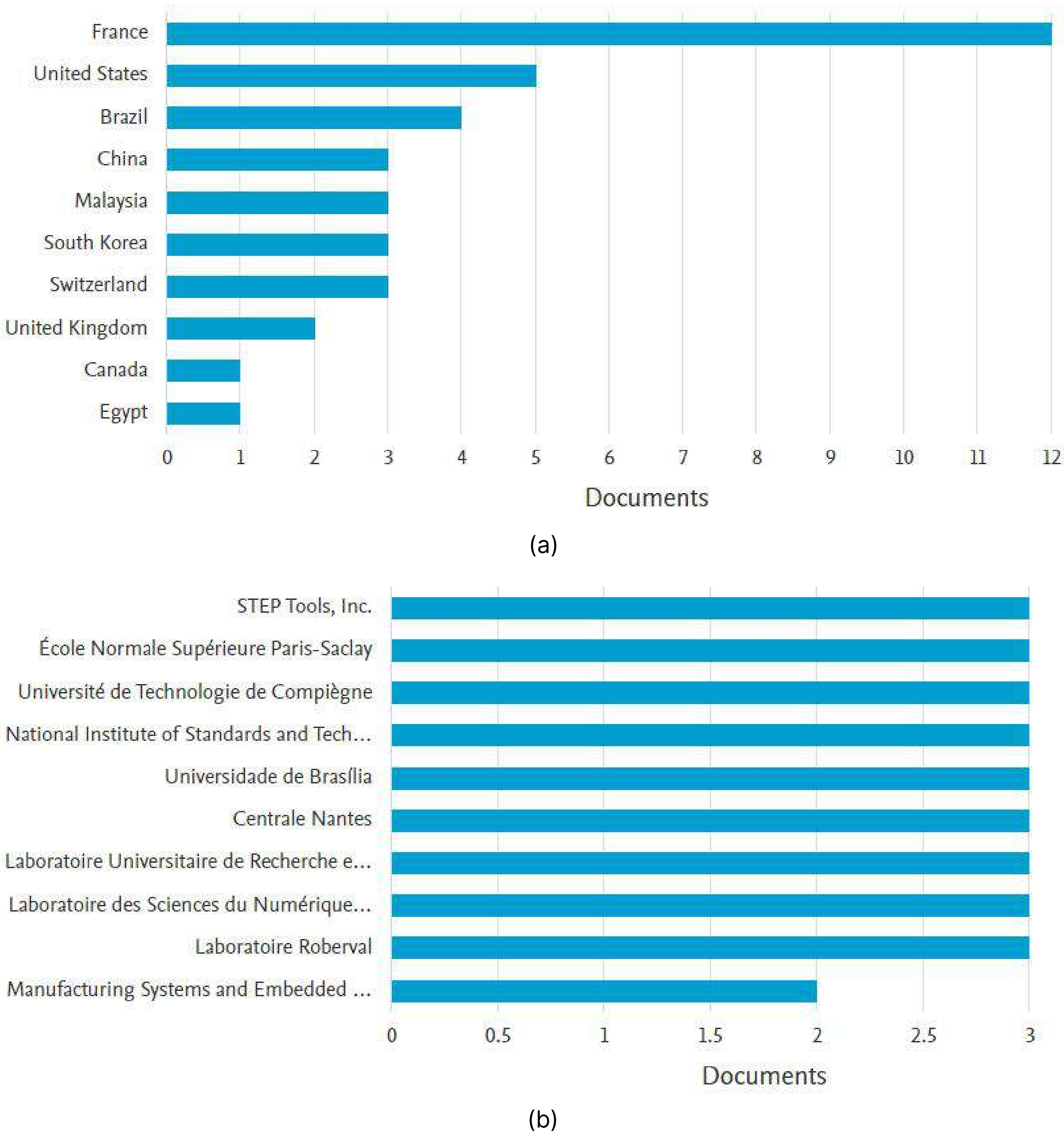


Figure 5.8: Additional statistics from the Scopus database regarding STEP-NC in AM (TITLE-ABS-KEY (("additive manufacturing" OR "3D printing" OR "rapid prototyping") AND ("STEP-NC" OR "ISO 14649" OR "ISO 10303-238" OR "AP238"))): (a) Documents by country; (b) Documents by affiliation.

consumption [316, 317, 318], closed-loop inspection [319, 320, 321], and robotic machining [322, 323, 324, 325], to name just a few. Conversely, the progress in AM processes has been relatively limited. The recent official release of the ISO 14649 Part 17 [294], developed by the ISO TC184/SC1 committee, represents a significant step forward, providing a comprehensive model for AM processes, including entities for detailing workingsteps, operations, features, and

AM technologies. However, ongoing development is essential to incorporate entities supporting specific AM technology parameters and operations.

5.3.1 STEP-NC data models and implementations in AM

Ryou et al. [326], in 2006, were early contributors to the development of a data model in EXPRESS language for AM aligned with the STEP-NC ISO 14649 standard. Their model featured three main categories: part geometric design data, part non-geometric design data, part process history, and (optionally) part locally controlled. However, it had limitations, lacking crucial information about AM technology specifics, tools, multi-material and multi-color design approaches, and manufacturing strategies. Despite being an initial effort, their model has not been incorporated into the standard, remaining at the proposal stage.

The work of Bonnard et al. [327, 328, 201] has been groundbreaking in proposing a holistic DTh/chain framework for AM based on STEP-NC. Their pioneering research, conducted at the École Centrale de Nantes in France between 2009 and 2010 [329, 327], laid the foundation for integrating STEP-NC data models tailored to address the inherent limitations of the AM DTh. These contributions align with the ISO 14649 standards set by the ISO TC 184/SC 1 working group, marking a significant milestone in the development of ISO 14649 Part 17.

In more recent works [330, 328], Bonnard et al. present substantial advancements in the implementation of STEP-NC information models, enabling the seamless exchange of data throughout the AM DTh. Their STEP-NC data model for AM integrates key elements such as task descriptions, geometry, product structure, and tools/technology. Building on the existing STEP-NC data model for machining (ISO 14649 Part 10), it incorporates AM-specific data, including material transformations (from powder, liquid, or solid to solid), machine tools (such as lasers or inkjet printheads), and environmental controls (like temperature, pressure, and humidity). The model also encompasses AM operations, strategies, and product structure, addressing the layered composition of AM products. Validated through the STEP-NC platform for advanced and intelligent manufacturing developed at École Centrale de Nantes, this model opens new avenues for advanced programming of AM machines. It also supports the integration of AM with other processes in hybrid manufacturing platforms, offering a flexible and robust framework for advancing the DTh in AM.

Building on their earlier work, Bonnard et al. [201] introduced the Hierarchical Object-Oriented Model (HOOM), a methodology grounded in object-oriented principles to address challenges in AM DTh. HOOM spans seven levels, encompassing the entire manufacturing process—from design to post-production—through a structured system of objects and instance variables. Tested in a STEP-NC-compliant digital chain, HOOM offers key benefits such as improved standardization, modularity, and interoperability.

Rauch et al. [74, 331] have introduced the concept of multi-process manufacturing, emphasizing the use of STEP-NC to integrate and supervise various manufacturing processes within a unified numerical chain. Their approach proposes a multi-process supervision platform that enables interoperability, computational simulation, and optimization of workplans across diverse processes. While this innovation allows cross-process interactions, they acknowledge the complexity of fully integrating such a multi-process system, as it requires significant efforts to develop an entirely connected digital chain. The data model in this system is designed to reflect modifications from each manufacturing stage, with STEP-NC acting as the unifying standard for various process data.

Um et al. [332] applied STEP-NC to AM in remanufacturing processes, emphasizing its ability to reduce production time and waste. However, they identified issues with surface quality and shape accuracy due to geometric errors in process planning. To overcome this, they proposed a STEP-NC-based process planning method that enhances part quality with accurate geometric representations and support for multiple materials. Their approach minimizes errors across the CAD-CAM-CNC chain, automates process planning, and considers tolerances. A case study validated this method, showing improvements in automation and surface quality.

Xiao et al. [333, 334, 215, 335], from the Université de Technologie de Compiègne, have also made significant contributions through a series of studies to the development and implementation of STEP-NC for AM. In one of their works [333], they present the definition, parameterization, and standardization of an information model for machine-specified AM processes based on STEP-NC. In a subsequent study [334], they focus on process planning and operations management in AM, by combining multiple standards, including ISO 10303, ISO 14649, ISO 15531, ISO/CD 18828, and the Unified Manufacturing Resource Model (UMRM), to integrate process implementations, manufacturing management, and control. Their objective is facilitate the automation of decision-making in process planning and operations management by providing essential information on machine tools and other resources. On the other hand, they also address the challenges of integrating geometric dimensioning and tolerancing (GD&T) into AM through product and manufacturing information (PMI) [215]. Their review examines the limitations of current geometric and tolerancing models, focusing on standards like STL, AMF, and STEP. They propose that STEP standards offer a strong foundation for advancing research and improving the integration, standardization, and management of geometric, material, and process data in AM.

In a separate study, Xiao et al. [335] introduced a comprehensive STEP/STEP-NC-compliant process data model tailored for FDM technology. This model defines key application objects and entities, establishing relationships, constraints, and standardizing process parameters within the context of 3D printing processes, which covers manufacturing layers, deposition operations, and process parameters. Specifically, manufacturing layers provide geometric details, while deposition operations define print devices, header paths, FDM technology, functions, and strategies. Additionally, the authors developed a conformance testing process, ensuring compliance through information exchange related to layers and header paths.

Pei et al. [336] evaluated existing additive manufacturing (AM) data transfer standards for their applicability in decentralized cloud manufacturing (RDM). They identified limitations in traditional formats like STL and explored alternatives such as AMF, 3MF, STEP, and STEP-NC. Through expert surveys and interviews, they found that STEP-NC and AMF are leading in incorporating essential features like internal structures, tolerances, and geometric representation. The study emphasizes the need for open standards to drive innovation in AM and urges policymakers and industry leaders to prioritize data exchange standards for a successful Digital Economy in RDM. Similarly, Lee et al. [337] provided an overview of ongoing AM standardization activities, focusing on IT aspects like data transfer and exchange. Their study highlights efforts from organizations like ISO TC261, ASTM International and the 3MF Consortium, noting that the manufacturing sector is at the forefront of these initiatives. The research also addresses emerging IT standards for AM service platforms and the medical field, emphasizing the need for standardized frameworks to support the broader adoption of AM technologies.

The authors of the present work have also contributed to the development of STEP-NC for AM within the research efforts conducted by Professor Alberto Alvares' team at the University of Brasilia, Brazil [214, 306, 305, 338, 321]. In an initial study, Rodriguez et al. [214, 306] introduced the concept of the AM layer feature to capture the geometric representation of each layer in an AM process. They proposed a STEP-NC data model focusing on entities related to the AM layer as main manufacturing feature in AM processes, which includes attributes such as layer thickness, build direction, and a list of contours (internal and external) described using a polyline. Although this concept is significant given the typically layer-by-layer nature of AM processes, it remains an early-stage model that does not encompass all aspects of information related to an AM feature. For instance, it lacks consideration of compound features, multi-material, and multi-color aspects, among other complexities.

Subsequently, the authors proposed a methodological approach for implementing STEP-NC in AM, adapting the existing STEP-NC data model, initially designed for machining processes [305]. The approach consisted of five core implementation steps: slicing the 3D part model into AM layers, generating an AM-specific STEP-NC program, constructing the kinematic model of the AM machine, simulating the AM toolpath, and validating the process by fabricating the part. The STEP-NC Machine software by STEP Tools, Inc. was employed to simulate the AM toolpath in conjunction with the 3D kinematic model of the machine. Prior to this, the STEP-NC program for AM was generated using the API from a custom-built C# application, which accessed a dynamic link library (DLL) provided by the STEP-NC Machine Software. For physical validation, a RepRap Mendel FDM 3D printer was used, equipped with an Arduino-based controller that interpreted the G-code generated from the conversion of the STEP-NC AM program. This approach not only demonstrated the practical feasibility of integrating STEP-NC in AM but also highlighted its potential to standardize process planning and enhance interoperability across AM systems. This approach was integrated with an MTConnect system for real-time process data access and remote monitoring over the Internet, as detailed in [338]

In another study [321], the authors present an integration strategy based on a STEP-NC digital data model for closed-loop control in AM. Their approach leverages STEP-NC models for both AM and inspection tasks, enabling a feedback loop within the AM DTh. The proposed architecture, validated using an open AM platform, demonstrates its ability to control errors in the manufactured parts, enhancing the efficiency and accuracy of the entire AM process.

Xiao and Lei [339] contribute to the integration and standardization of AM part structures by proposing an architecture based on STEP-NC Part 17. They categorize AM layer features, such as general geometry, foam structure, honeycomb structure, and lattice structure, with detailed parameters. Their work emphasizes optimal process parameters for improved interoperability and introduces a specific STEP/STEP-NC-compliant data model. Additionally, they provide conformance analysis and implementation insights for various application systems.

Um et al. [340] demonstrated that using STEP-NC in AM significantly improves data accuracy and tool-path generation. Their boundary representation (B-Rep) and squashing algorithms prevent volume loss, ensuring precise shape construction, concluded from a case of industrial plastic products. The method surpasses traditional tessellated approaches and shows promise for hybrid manufacturing, combining additive and subtractive techniques.

Milaat et al. [296] identified shortcomings in the existing STEP-NC data representations for AM and proposed an enhanced data model specifically designed for PBF processes. Their work focused on refining the representation of process parameters by defining interlayer relationships, along with the technology and scan strategy controls. As previously mentioned, the entities introduced by Milaat et al. served as a foundational basis for the development of the data model part dedicated to PBF processes, which is now being incorporated into fourth edition of AP238. Building on this work, Milaat et al. [341] propose a model that enables point-level control and process definition in AM through new data representations within the STEP-NC standard. This approach facilitates comprehensive volumetric inspection during both fabrication and post-processing of AM parts. By incorporating key concepts such as "authoritative product definition" and DTw, their methodology aims to streamline AM process qualification, enhance data traceability, and enable reliable real-time control, ultimately improving part acceptance in advanced manufacturing settings.

Latif et al. [342] introduce a methodology utilizing the STEP-NC data interface model for 3D printing, leveraging CAD data from either the ISO10303 or ISO 14649 data interface model in Part 21 of the physical file representation. They developed a system to generate tool paths for 3D printing using STEP-NC Part 21, implemented on a 3D printer through indirect and interpreted programming techniques. The system employs virtual component technology and a specific algorithm to control tools for 3D printing operations.

The most recent work to date addressing STEP-NC in AM is presented by Xiao et al. [343], who conducted a comprehensive review on the integration of STEP-NC standards within the AM DTh. Their study explores how STEP-NC, originally designed for CNC processes, can be adapted to AM to enhance data interoperability and knowledge discovery through ontology-based approaches. By combining STEP-compliant data transfer with knowledge-driven methods, their work proposes a pathway for improving the efficiency of AM processes, enabling intelligent support for industrial applications and facilitating more effective decision-making in AM systems.

Table 5.3 organizes the reviewed studies on the application of STEP-NC in AM processes by research groups, highlighting ongoing contributions from certain teams. The table provides detailed information on each study, including the country of the research team, publication years, specific research focus, the STEP-NC standard employed, and the type of AM process explored. This structured summary allows for a clearer view of how different groups are advancing the integration of STEP-NC in AM, often through a series of interrelated works.

While significant advancements have been made in the literature, several challenges remain in translating these concepts into practical, industrial-scale applications. To facilitate widespread adoption, further work is required to integrate STEP-NC seamlessly with AM technologies. In particular, the development of robust STEP-NC implementation architectures tailored specifically for AM is essential, with a focus on real-time data validation and aligning with key Industry 4.0 concepts such as the DTh and DTws.

5.4 Short Survey on STEP-NC Implementation Architectures

The development of robust implementation architectures is essential for realizing the full potential of STEP-NC in manufacturing processes. These architectures serve as the foundation for integrating STEP-NC data models with manufacturing technologies, ensuring seamless communication between digital design and manufacturing processes. Latif et al. [344] conducted an extensive literature review emphasizing the critical need to advance the development of STEP-NC implementation architectures, particularly through their integration with a variety of modern technologies. They highlight the potential of combining STEP-NC with microcontrollers, Arduino, LabVIEW, MATLAB, Python, Java, C, and other hardware and software platforms to create cost-effective CNC systems and prototypes. This integration is essential for driving future innovations and enabling low-cost, flexible solutions that can meet the evolving demands of CNC systems.

Suk et al. [345] introduced three types of STEP-NC implementation architectures for CNC systems: conventional control, new control, and new intelligent control. The conventional control integrates ISO 14649 into legacy CNC systems via post-processing, converting STEP-NC data into G-code, enabling its use in older machines. The new control goes beyond this by directly utilizing STEP-NC data for tool path generation, eliminating the need for G-code and improving automation, but still lacking real-time feedback. The new intelligent control represents the most advanced model, integrating real-time process data to dynamically adjust machining parameters and tool paths during operation, fully exploiting STEP-NC's potential for adaptive manufacturing.

Table 5.3: Summary of reviewed research works on STEP-NC in AM processes.

Research	Country	Year	Focus	Standard	Process
[326]	South Korea	2006	New AM data model in EXPRESS	ISO 14649	Binder jetting, photopolymers, direct metal deposition
[329, 327]	France	2009-2010	AM digital chain based on STEP-NC	ISO 14649	Laser cladding
[330, 328, 201, 186]	Brazil, France, Switzerland	2018-2019	New STEP-NC data model for AM Digital Thread	ISO 14649	Laser cladding, FDM
[74, 331]	France	2012-2014	Multi-process concept with STEP-NC	ISO 14649	Laser cladding, multi-process
[333, 334, 215, 335]	France	2017-2021	STEP-NC model for AM	ISO 10303, ISO 14649	FDM
[332]	France, Switzerland	2017	STEP-NC process planning for remanufacturing	ISO 14649	Laser cladding, remanufacturing
[336, 337]	UK, France, S. Korea, Germany	2019	Investigation review	ISO 10303, ISO 14649	General
[214, 306, 305, 338, 321]	Brazil	2017-2019	STEP-NC process planning for AM	ISO 10303-238, ISO 14649	FDM
[339]	China	2022	STEP-NC for AM feature representation	ISO 14649	General
[340]	South Korea, Switzerland	2022	Slicing algorithm	ISO 14649	General
[296, 341]	USA, France	2022-2023	New data model for PBF process	ISO 10303-238	PBF
[342]	Malaysia	2023	STEP-NC for 3D printing interface	ISO 14649	FDM
[343]	France, China, Brazil	2024	Review on STEP-NC AM Digital Thread	ISO 14649, ISO 10303	General

Rauch et al. [74] built upon the three architectural types by categorizing STEP-NC implementations into indirect (Figure 5.9 (a)), interpreted (Figure 5.9 (b)), and adaptive programming (Figure 5.9 (c)). The indirect method uses an interpreter to enable STEP-NC compatibility with legacy CNC controllers, making G-code or robot-specific language (as proposed in [322, 324]) invisible to the user. The interpreted method directly executes commands from STEP-NC files, incorporating external data, such as probing results, for more precise tool path control. Lastly, the adaptive method, the most advanced, continuously optimizes machining parameters in real time, pushing toward fully autonomous manufacturing. However, this approach faces challenges, particularly in the development of robust experimental platforms and prototypes.

Latif et al. [310, 346] propose a hybrid approach (Figure 5.9 (d)) that combines elements of both the indirect and interpreted methods described by Rauh et al. This approach leverages an expert system composed of four key modules: mining, generating, output, and execution. These modules work together to extract data from STEP-NC machining programs, enabling automated decision-making capabilities in areas such as data mining, tool path generation, and machine execution. Once the data is extracted, the algorithm performs an analysis and provides interpretation recommendations, which can involve indirect, interpreted, or hybrid approaches depending on the scenario. The system's database stores these interpretations, along with algorithms for generating tool paths for various manufacturing operations, such as facing, pocketing, drilling, and contouring, among others. This structure enables a flexible, data-driven approach to optimize machining processes through STEP-NC technology.

Xiao et al. [347] propose a STEP-NC-enabled edge–cloud collaborative manufacturing system designed to enhance CNC machining by improving data traceability and intelligent process analysis (See Figure 5.9 (e)). Their system integrates edge-side intelligence for real-time data acquisition, understanding, and simulation of CNC machining, while cloud-side capabilities manage big data and enable advanced services such as task distribution and virtual monitoring. This approach allows for a more dynamic and precise connection between design and manufacturing, using workstep-tagged data to improve traceability. Tested in a COMAC workshop, the system demonstrated its feasibility for large-scale industrial application, offering a path toward smarter, more adaptive CNC machining processes.

This thesis work proposes a new architecture that takes the form of a digital ecosystem for AM driven by standards-based DTh and DTw, which is presented in Chapter 6.

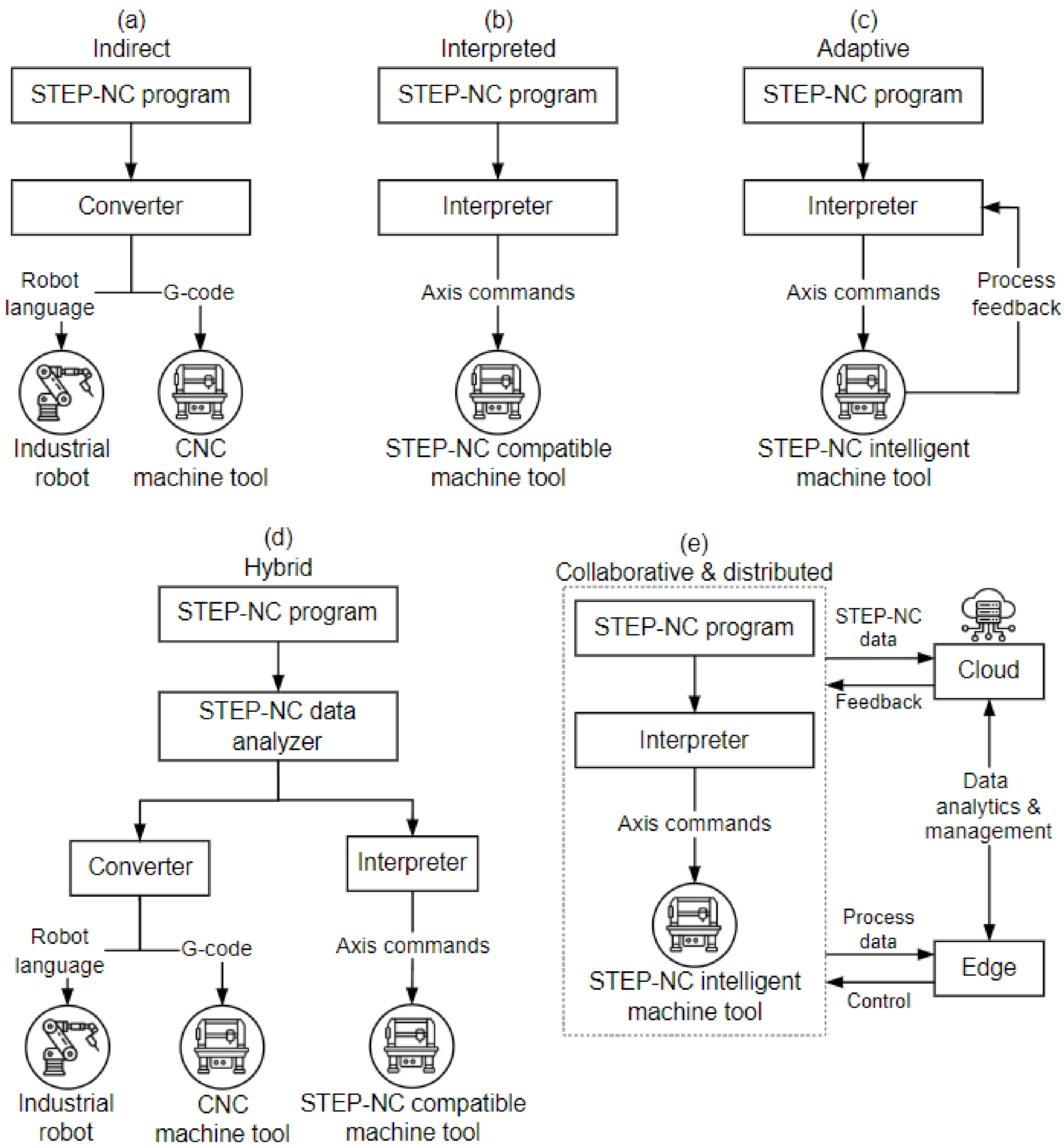


Figure 5.9: STEP-NC architectures in literature: a) Indirect; b) Interpreted; c) Adaptive; d) Hybrid; e) Collaborative.

Chapter 6

Towards a Digital Ecosystem for AM driven by Standards-based Digital Thread and Digital Twins.

6.1 Unified digital ecosystem for contextualized intelligence

As detailed in Chapter 3, the DTh represents a continuous flow of data generated, processed, and exchanged across various stages of the manufacturing lifecycle. Each stage—ranging from design to inspection, and beyond—produces a wealth of information, encapsulating everything from geometrical specifications and process parameters to real-time performance metrics and quality assurances. This interconnected data stream, conceptualized in Figure 6.1, not only enables a comprehensive understanding of the manufacturing process but also creates opportunities for integrating DTw at every phase.

The power of a DTw lies in its ability to replicate and augment the physical counterpart it represents, performing functions that range from real-time monitoring to predictive simulations. When tied to a specific phase of the DTh, a DTw can optimize processes within that phase. For instance, in the design phase, the DTw can analyze geometry, material properties, and manufacturability constraints, providing feedback on potential design flaws or improvements. During process planning, a DTw could simulate tool paths, optimize process parameters, and predict bottlenecks, improving overall efficiency. In the manufacturing phase, the DTw can monitor production in real-time, detect deviations from planned processes, and adapt operations to prevent defects. Finally, in the inspection phase, a DTw can compare actual quality metrics with design specifications, identify anomalies, and guide corrective measures.

The true potential of DTw can be unlocked when they leverage contextualized data across the entire DTh. A Design DTw, enriched with insights from manufacturing and inspection,

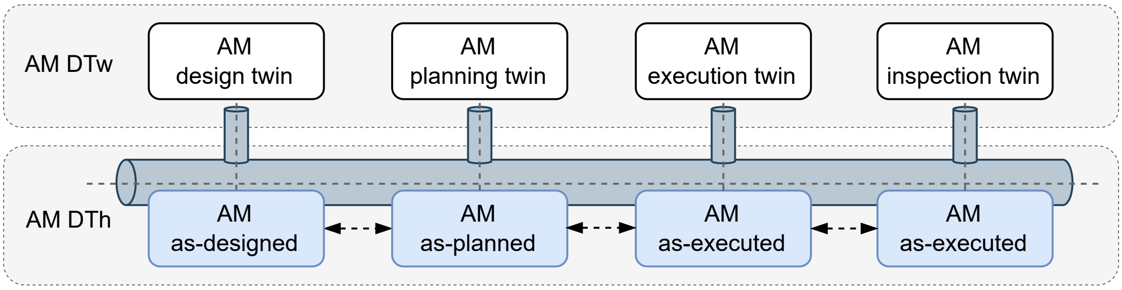


Figure 6.1: Concept of an AM Digital Thread connected with Digital Twins.

could recommend design alterations to enhance manufacturability and ensure quality compliance. Similarly, an Inspection DTw, armed with data on design intent and manufacturing conditions, could perform root-cause analysis of defects, enabling closed-loop quality improvements. By transcending phase-specific applications, these interconnected DTws drive holistic advancements across the manufacturing lifecycle.

Let DTh_i represent the i-th DTh, where $i \in \{1, 2, ..., n\}$. Each thread is a collection of datasets representing lifecycle information across phases, such as design (d), planning (p), manufacturing (m), and inspection (q):

$$DTh_i = \{d_i, p_i, m_i, q_i\}$$

The relationship between DThs and DTws can be expressed as

$$DTw_j = f(DTh_1^{c_1}, DTh_2^{c_2}, ..., DTh_n^{c_n}),\ \forall j \in \{1, 2, ..., m\}$$

Where,

- DTw_j: The j-th DTw that aggregates and contextualizes data from multiple DThs.
- f: A function describing how data from various DTh is utilized by the DTw_j, encompassing tasks such as monitoring, optimization, or simulation.
- c_i: is a contextual filter applied to DTh_i, determining which lifecycle data (e.g. d_i, p_i, m_i, q_i) are relevant.

Now, the total set of DTw in the system can be expressed as:

$$\{DTw_1, DTw_2, \ldots, DTw_m\} = \bigcup_{j=1}^{m} f_j(DTh_1^{c_1}, DTh_2^{c_2}, \ldots, DTh_n^{c_n})$$

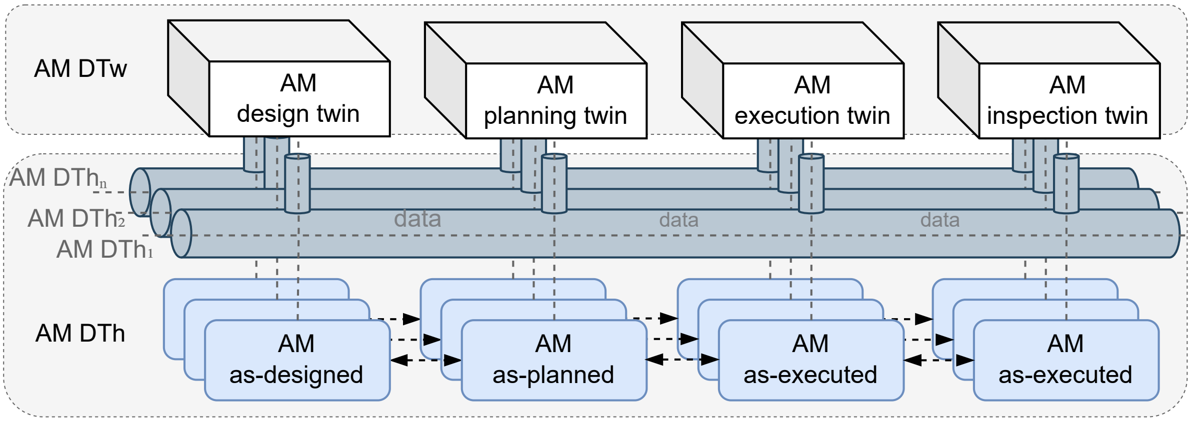


Figure 6.2: Concept of Multi-Threaded data flow interconnected with Digital Twins for cross-context lifecycle analysis.

This formulation captures the unification of DTws and their interaction with multiple DThs to perform targeted analyses and operations. For example, consider a manufacturing scenario that involves two DThs: DTh_A, representing an additive manufacturing process, and DTh_B, representing a subtractive manufacturing process. DTh_A contains layer-by-layer deposition rates and thermal profiles, while DTh_B includes toolpath efficiency and cutting forces. A manufacturing DTw (DTw_M) can synthesize data from DTh_A and DTh_B to predict scheduling conflicts, identify material interactions, and suggest parameter adjustments for optimized workflow. Simultaneously, an inspection DTw (DTw_Q) could leverage defects data from both threads to diagnose systemic issues, propose corrective measures, and improve quality control.

This multi-threaded approach exemplifies the transformative potential of DTw when contextualized across interconnected DThs. By integrating and analyzing data streams from diverse lifecycles, DTw drive holistic optimization, enabling advanced predictive capabilities, adaptive decision-making, and enhanced efficiency throughout the manufacturing ecosystem. This vision naturally leads to the proposition of a unified digital ecosystem for contextualized intelligence, where seamlessly integrated DThs and DTws, underpinned by standardized technologies and frameworks, provide a cohesive foundation for smarter, more adaptive manufacturing processes.

6.1.1 Contextualized data storage

In this approach, data storage must account for the dynamic and cyclical nature of manufacturing lifecycles, where DTh are applied iteratively across various phases. Each DTh represents a structured sequence of lifecycle stages—design, process planning, manufacturing, and inspection—where different information systems interact to generate and manage data. As a DTh is repeatedly applied to the lifecycle of a product or process, it creates a rich historical record, linking specific instances of the DTh to their corresponding lifecycle events. A robust database architecture should be capable of linking each DTh to its historical applications, ensuring traceability and enabling cross-thread analysis. For example, a relational database could model each DTh as a parent entity, with lifecycle instances stored as child records that detail the specific systems, parameters, and outcomes for each phase. Shared phases, such as a common design or inspection process, can be referenced across multiple DTh to minimize redundancy and enhance interoperability. Moreover, temporal data from each DTh's application must be stored in a way that supports retrospective and predictive analysis. This could involve time-series databases that log dynamic changes during real-time operations, ensuring that DTw have access to contextually rich, chronologically ordered datasets for monitoring and simulation.

6.1.2 Challenges of the proposed unified ecosystem

Despite the promising potential of a unified digital ecosystem for contextualized intelligence, its full realization is critically dependent on the availability and efficient management of manufacturing data throughout the DTh. However, significant challenges persist in achieving this ideal. The lack of a comprehensive and standardized data representation framework has led to persistent issues within manufacturing DTh—particularly in AM—including information loss, redundancy, and disconnections caused by interoperability gaps. These problems are exacerbated by low intelligence at the CNC level, fragmented DTh lacking real-time feedback, and inefficiencies in leveraging the data for actionable insights.

While the integration of DTh and DTw technologies promises to inject higher levels of intelligence and adaptability into manufacturing systems, it can also inherit the underlying limitations of the DTh. For instance, an incomplete or poorly managed DTh risks propagating inaccuracies or introducing bottlenecks into the broader ecosystem, undermining the transformative potential of DTw. This underscores the necessity for a robust digital ecosystem driven by standards-based DTh and DTws. To realize this vision, it becomes essential to define a cohesive set of standards aligned with the requirements of this ecosystem. Based on the literature review and analysis presented earlier, several standards with significant potential have been identified. These standards, which are discussed in the subsequent section, form the foundational building blocks for defining a comprehensive digital ecosystem. They aim to address current challenges while laying the groundwork for a seamless integration of DTh and DTws in advanced manufacturing processes.

6.2 Proposal of a digital ecosystem for AM driven by standards-based DTh and DTw

This work proposes a cutting-edge digital ecosystem that leverages the power of the DTh and DTw to seamlessly integrate the physical and digital worlds, as depicted in Figure 6.3. Based on the comprehensive review of literature presented in previous chapters, several key standards have been identified, serving as foundational pillars upon which this digital ecosystem is built. This integration of standards not only enhances the quality and reliability of information management but also fosters interoperability and collaboration within the broader industrial landscape. Through adherence to established norms and guidelines, the proposed digital ecosystem seeks to propel the advancement and adoption of AM technologies while addressing key challenges and promoting best practices in the field. However, this digital ecosystem architecture is not only designed for AM but is also applicable to general manufacturing processes.

The concept of the digital ecosystem is aligned with the vision of the ISO 23247 framework, which provides a comprehensive DTw architecture framework tailored for industrial manufacturing applications. This architecture begins in the physical space, where traditional manufacturing tools, such as CAD systems, CAPP/CAM platforms, CNC machines, and maintenance systems, form the foundation of production, aligning with the OMEs (Observable Manufacturing Elements) layer of ISO 23247. However, the true value is unlocked when these systems are integrated with the DTh, a continuous flow of data that captures each phase of production, known as the Digital Thread Entity (DThE) in the Part 5 draft of ISO 23247 [235].

Production of an AM part begins with the receipt of customer requirements, which are then passed on to the design engineer for the creation of the CAD model of the part. This entails incorporating various data elements such as 3D or 2D geometry of the part, or even a point cloud obtained from a scanned part. Additionally, data from the tessellated 3D model, GD&T requirements, material specifications, among others, may also be integrated. This collection of data is commonly referred to as "as-designed" data and is transmitted through the design thread, a channel proposed to be supported by a model-based data format such as STEP, encompassing AP203, AP214, or the more comprehensive AP242. AP242, in particular, facilitates AM design by incorporating entities to represent tessellated geometry and curved tessellated geometry.

The "as-designed" data forms the cornerstone for subsequent phases of the process. During the CAPP/CAM phase, the process planning engineer can use these data to generate a comprehensive process plan. This involves leveraging the feature-based manufacturing approach from STEP 224 [282], along with STEP-NC (either ISO 14649 or ISO 10303 AP238, where AP 238 seamlessly integrates with other STEP's APs). In addition, the engineer is tasked with selecting the appropriate AM technology, setting process parameters, determining the optimal orientation of the part, and selecting support materials if necessary. Ultimately, simulation of the process plan is conducted to validate the planned process conditions. All of these steps constitute the

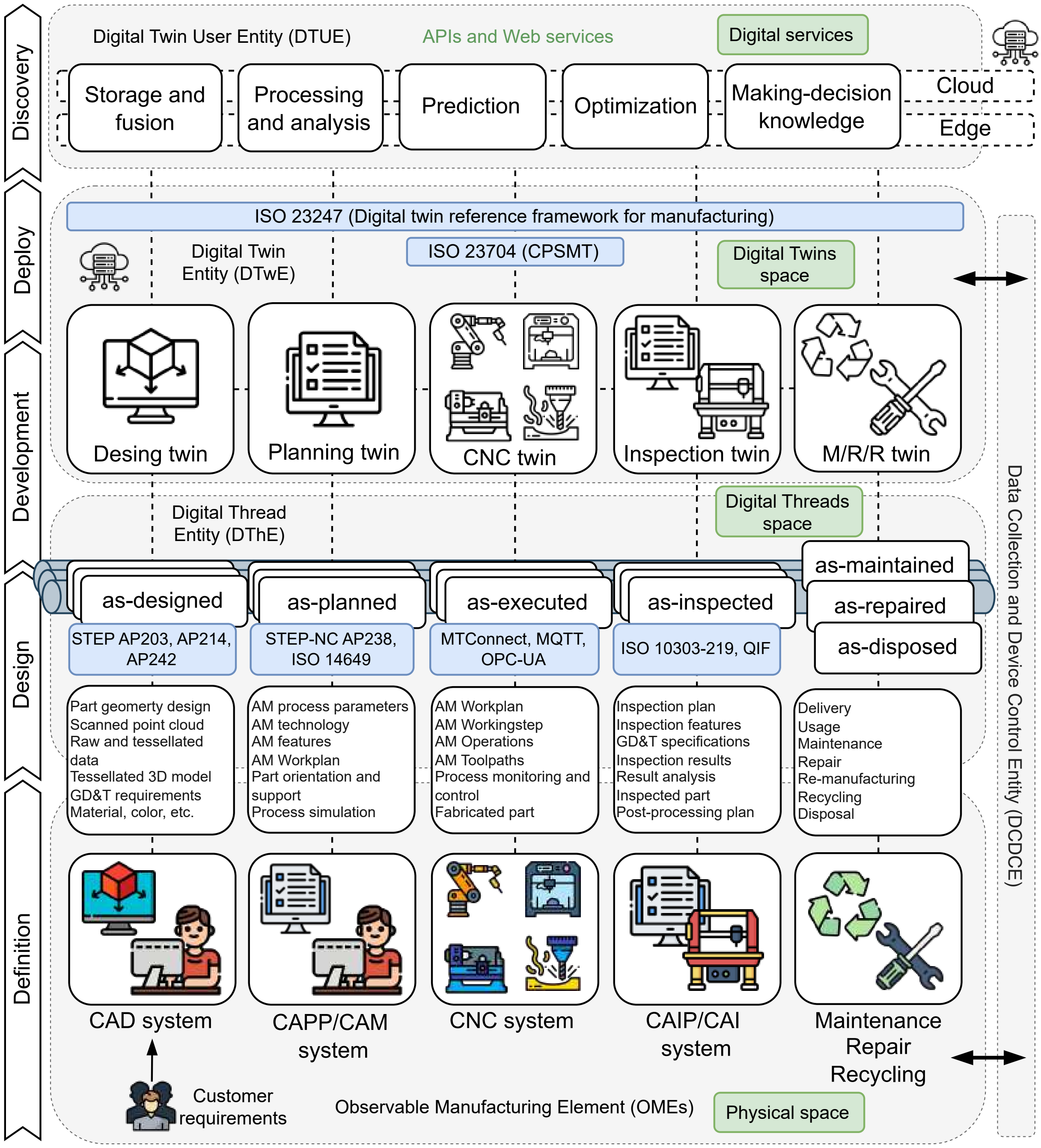


Figure 6.3: Digital ecosystem framework for AM driven by standards-based Digital Thread and Digital Twin.

"as-planned" data transmitted through the process planning thread, which is supported by STEP and STEP-NC in this proposed ecosystem.

In the subsequent CAM/CNC phase, the process plan is handed over to the operator engineer of the AM CNC system for execution, adhering workinstep by workinstep within the proposed workplan outlined by the STEP-NC standard. Each workinstep corresponds to a specific manufacturing feature requiring an AM operation as per ISO 14649 Part 17. During this phase, toolpaths may have been previously generated in the process planning phase or can be generated for each operation by the CAM/CNC system. This represents the “as-executed" data going through the manufacturing thread supported essentially by the STEP-NC data model. Validation of the generated toolpaths can be achieved through simulation. Process monitoring and machine condition monitoring are conducted by gathering data through the machine controller and external sensors. This data is then transmitted over the network using protocols such as MTConnect, OPC UA, or MQTT. Additionally, control over the AM system can be facilitated through protocols like OPC UA or MQTT, enabling bidirectional data flow. The outcome of this phase should be the completion of the manufactured part, poised for subsequent post-processing and inspection.

Within the CAIP/CAI system, the inspection phase uses a variety of measurement tools, including Coordinate Measuring Machines (CMM), to ensure that the manufactured part meets both GD&T requirements and surface finish specifications. This meticulous inspection process is performed on the basis of a comprehensive inspection plan crafted by a dedicated inspection engineer. Using the feature-based inspection methodology outlined in STEP AP 219 [283] and STEP-NC standards, the engineer ensures a thorough examination. Furthermore, to effectively represent the inspection plan and manage the inspection results, the industry-standard QIF and DMIS formats can be employed. Real-time transmission of measurement results across the network is facilitated by communication protocols such as MTConnect, OPC UA, or MQTT. This are the “as-inspected" data. The culmination of this phase is the generation of a comprehensive inspection report through the CAI system. Should adjustments be necessary, such as refining dimensions, tolerances, or surface finishes, the part may proceed to a subsequent phase of process planning for postprocessing.

Other several crucial phases of the AM process lifecycle can relate "as-maintained," "as-repaired," and "as-disposed" data. In the "as-maintained" stage, data tracks the ongoing condition and performance of the product during its usage, managed by maintenance professionals who ensure its optimal functionality. Transitioning to the "as-repaired" phase, the data record any maintenance or repair activities undertaken to address issues or failures, facilitated by maintenance or repair specialists. Hybrid manufacturing techniques can play a pivotal role in this phase, particularly in the context of remanufacturing. This approach combines traditional repair methods with advanced AM processes to restore components to their original specifications or even enhance their performance. By leveraging hybrid manufacturing in the "as-repaired" phase, remanufacturers can achieve greater flexibility, efficiency, and sustainability in the restoration of components, ultimately prolonging their lifecycle and reducing overall waste. These activities are often guided by standards such as ANSI RIC001.2, ISO 55000 for asset management, ISO 14000 for environmental management, and ISO 15270 for recycling management. Subsequently, in the "as-disposed" phase, data oversee the recycling or disposal of the product at the end of its lifecycle, overseen by professionals in logistics or product management, ensuring environmentally responsible practices are upheld throughout the process, from delivery to disposal.

Table 6.1 provides an overview of the key standards grouped by their application within the DTh stages and their relevance to DTw and CPS frameworks. These standards could collectively enable efficient data exchange, real-time monitoring, and enhanced decision-making across the manufacturing lifecycle.

Table 6.1: Key standards for the proposed digital ecosystem.

Domain/Phase	Standards and Description
Design	**STEP ISO 10303 - AP203, AP214, AP242**: Enable rich product data exchange, including geometric and model-based information for AM design processes.
Process Planning	**STEP-NC ISO 14649, ISO 10303 - AP238**: Support intelligent CNC programming, linking design and manufacturing through feature-based definitions and process plans.
Manufacturing execution	**MTConnect (ANSI/MTC1.4), OPC-UA, MQTT (ISO/IEC 20922), ISO 14649, ISO 10303 AP238**: Facilitate real-time communication, process monitoring, and machine data collection during AM execution.
Inspection	**ISO 10303 - AP219, QIF (ISO 23952)**: Ensure traceable quality control and inspection by linking measurement data to design specifications.
DTw/CPS frameworks	**ISO 23247, ISO 23704**: Provide reference architectures and frameworks for integrating DTw and CPS in manufacturing environments, supporting data synchronization and real-time monitoring.

A key advantage of this architecture is the role of STEP-NC models, which incorporate entities specifically for AM, machining, or multi-process definitions. These models allow for detailed descriptions of AM operations and process parameters, ensuring that every aspect of the technology is captured. This data can be used not only to generate STEP-NC programs for machine controllers but also to provide an essential context for DTw. By combining real-time machine condition and process data gathered via MTConnect, MQTT, or OPC-UA, DTws are enriched, enabling deeper simulation, monitoring, and optimization of products and manufacturing systems. This creates a feedback loop where the physical and digital realms work together to drive continual improvement, enhance decision-making, and optimize performance across all stages of production. The Data Collection and Device Control Entities (DCDCE) module further enhances this integration by synchronizing the OMEs entities with DTw entities, effectively overseeing sensor data and managing actuated devices within the OME domain.

Each stage of the DTh (as-designed, as-planned, as-executed, as-inspected, as-maintained) is seamlessly mirrored in the digital twins space by corresponding DTw, virtual replicas of their physical counterparts. The digital twins space, equivalent to a cyber space, incorporates the Digital Twin Entity (DTwE) as defined within the ISO 23247 framework, which is the core at this architecture. These twins, such as the design twin, process plan twin, CNC twin, and inspection twin, act as real-time reflections of their respective physical processes. This mirroring allows manufacturers to simulate, predict, and optimize outcomes long before committing physical resources, creating a digital ecosystem that ensures efficiency, flexibility, and resilience across the entire manufacturing lifecycle. For instance, the design twin serves as a virtual representation of the CAD model or design specifications of the part to be manufactured. It allows designers and engineers to simulate various design iterations, analyze structural integrity, and optimize geometries for AM processes. Furthermore, enables real-time collaboration and visualization of design changes, facilitating rapid prototyping and design validation leveraging integrated data from subsequent phases.

Similarly, the process planning twin encompasses the digital representation of the part's geometry, support structures, and build orientation, optimized for AM. It enables process simulation, slicing, and toolpath generation, allowing operators to optimize build parameters, minimize material usage, and reduce build time. The DTw provides insights into the feasibility and manufacturability of the part, guiding decision-making during process planning activities.

The manufacturing twin operates as a virtual replication of the physical AM process, offering a detailed simulation of material layer construction, thermal behavior, and cooling dynamics throughout fabrication. This virtual environment enables real-time monitoring and precise control over AM parameters, ensuring strict adherence to quality standards while minimizing the occurrence of defects. Operators benefit from the ability to scrutinize process deviations, forecast potential build failures, and refine fabrication strategies, thereby enhancing both part quality and production efficiency. Furthermore, the manufacturing twin encompasses the monitoring of machine condition, leveraging data collected from the shop floor through communication protocols such as MTConnect, OPC UA, or MQTT. By amalgamating this real-time data with historical records, manufacturers can conduct sophisticated analyses utilizing machine learning and big data analytics, thereby improving overall process conditions and predicting machine behaviors with greater accuracy and foresight.

Moreover, the inspection twin is dedicated to monitoring and assessing the quality of AM parts throughout the production cycle. It integrates data from in-line sensors, non-destructive testing, and metrology equipment to track dimensional accuracy, surface finish, material properties, and defect detection. This twin enables real-time quality control, anomaly detection, and root cause analysis, empowering operators to identify and address quality issues proactively. Additionally, it supports traceability and documentation of quality metrics for compliance and certification purposes.

Furthermore, maintenance, repair, and recycling twins extends beyond the manufacturing phase to encompass the operational lifecycle of AM parts. It monitors part performance, usage conditions, and environmental factors affecting durability and reliability. It enables predictive maintenance, prognostics, and lifetime estimation, allowing stakeholders to optimize asset management strategies and maximize operational uptime. By capturing real-world operating conditions and feedback, this DTw facilitates continuous improvement and optimization of AM processes for enhanced lifecycle performance.

The ISO 23247 standard facilitates the systematic development of DTws, aligning their creation with established industry best practices. In addition, the ISO 23704 [138] series outlines critical requirements for smart machine tools, facilitating the advancement of smart manufacturing on the shop floor through a cyber-physical control framework. Notably, Part 3 of this series is dedicated to AM machines [140]. Collectively, these standards empower manufacturers to develop robust and effective Digital Twins.

The final layer of this architecture is the digital services space, which includes the Digital Twin User Entity (DTUE). Here, data from Digital Twins is leveraged for virtual monitoring, analytics, prediction, optimization, and decision-making. Through cloud-based APIs and web platforms, manufacturers can integrate data from various sources to anticipate maintenance needs, optimize production schedules, and foster real-time innovation. This dynamic environment not only enhances operational efficiency but also empowers organizations to make data-driven decisions that drive growth, improve product quality, and maintain competitiveness in an ever-evolving market.

Finally, the left side of the Figure 6.3 illustrates the 5D product design process as proposed by Aheleroff et al. [227]. The first section, titled “Definition," is situated entirely within the physical space, underscoring the critical role of establishing clear requirements and specifications at the project’s inception. Next, the “Design" section signifies the start of the Digital Thread, marking the transition from tangible concepts to digital representations. The “Development" section extends from the Digital Thread into the digital twins space, emphasizing the integration of both physical and digital elements throughout the product’s evolution. Moving further into the cyber realm, the “Deploy" section concentrates on the effective implementation of these digital assets. Finally, the “Discovery" section, located within the digital services division, highlights the importance of leveraging data-driven insights and analytics to enhance product performance and drive innovation.

6.2.1 Benefits and Challenges of the Proposed Ecosystem

The integration of DTh and DTw within the proposed digital ecosystem is envisioned to have the potential to revolutionize manufacturing processes, although it is not guaranteed and depends on successful implementation and adoption. It is expected to address several key areas:

- Data Integration: The framework is expected to enable seamless access to data, including design specifications, process parameters, and machine conditions, ensuring coherence and accessibility across all lifecycle phases.
- Interoperability: Leveraging standardized protocols could facilitate smoother communication and collaboration among diverse systems and technologies, reducing compatibility

issues and fostering a more cohesive manufacturing environment.

- Bidirectional Data Flow: The framework aims to establish horizontal communication between manufacturing stages and vertical integration between shop floor operations and higher-level management systems, enabling more agile and responsive decision-making.
- Closed Feedback Loops: DTw have the potential to provide real-time insights, linking performance data from manufacturing back to earlier lifecycle phases like design, supporting iterative optimization and innovation.
- Enhanced CNC Controller Intelligence: By integrating DTw with STEP-NC, the framework could allow for adaptive machining parameters and toolpath adjustments in real time, potentially improving precision, efficiency, and process reliability.
- Model-Based Definition Advantages: The use of model-based definitions is anticipated to enable precise representations of complex geometries and tolerances, leading to higher accuracy in manufacturing outcomes and reduced reliance on manual corrections.
- Contextual Enrichment: DTw enriched with domain-specific and lifecycle data are expected to enhance predictive capabilities and adaptability, enabling smarter responses to operational variations.
- Innovation Potential: Advanced analytics, combined with machine learning and big data, may unlock novel solutions for optimizing processes, driving innovation in product design, and maintaining a competitive edge.
- Sustainability: The framework has the potential to contribute to more sustainable practices by improving resource efficiency, enabling predictive maintenance, and extending product lifecycles through enhanced repair and remanufacturing strategies.

However, realizing this framework involves significant challenges. The complexity of integrating DTh and DTw across an entire ecosystem may demand substantial investments in software, hardware, and personnel training. Data integration efforts must align with existing organizational workflows, and resistance to change may impede adoption. While these hurdles are nontrivial, the potential gains in efficiency, quality, and innovation make this framework a strategic investment for manufacturers aiming to thrive in the rapidly evolving landscape of smart manufacturing.

To contribute to the advancement of implementations aligned with the vision of the proposed digital ecosystem, Chapter 7 introduces a series of practical case studies developed as part of this thesis. These cases illustrate key methodologies and strategies for integrating standards such as STEP, STEP-NC, MTConnect, OPC UA, MQTT, and QIF within an AM digital ecosystem, offering an actionable foundation for further exploration and innovation in this domain.

Chapter 7

Practical Implementations

This chapter presents five implementation scenarios developed to validate the contributions of this thesis within the proposed digital ecosystem for AM:

- **Robotic Machining:** Using STEP-NC to generate and simulate toolpaths for an ASEA robotic arm with a milling spindle.
- **STEP-NC and MTConnect in AM:** Integrating STEP-NC with MTConnect for real-time monitoring of an FDM process on a RepRap 3D printer.
- **LMD and STEP-NC Simulation:** Simulating toolpaths for LMD using STEP-NC with a virtual model of the KUKA KR70 robot and a Meltio printhead.
- **Proposed STEP-NC Data Models:** Defining new STEP-NC entities tailored for FDM and LMD processes to manage layer-specific data.
- **TypeScript-Based STEP-NC Library:** Developing an open-source, extensible library to facilitate the creation and management of STEP-NC models.

7.1 Scenario 1: STEP-NC implementation method for industrial robotic machining

This implementation scenario focuses on demonstrating the use of STEP-NC for robotic machining, using an ASEA IRB6-S2 robot with 5 DOF, controlled by an open LinuxCNC controller. Beyond technical implementation, this work explores practical methods for applying STEP-NC, evaluates available tools, and identifies areas for improvement in the adoption of this technology toward implementation in AM. STEP-NC (ISO 10303-AP238) provides a standardized approach to address challenges such as the complexity of programming and simulating robotic machining operations, allowing the generation of contextualized machining programs for this application.

The activity flow for implementing this scenario is illustrated in Figure 7.1 using an IDEF0 diagram, detailing four core activities (A1–A4), while Figure 7.2 depicts the corresponding workflow illustrating each activity. The process begins with CAD modeling and toolpath generation, where Mastercam, Siemens NX, and PTC Creo are used to model the test part and define machining operations such as facing, roughing, and pocketing. These operations include key parameters like feedrate, spindle speed, and tool geometry. CAD/CAM tools enable simulation of the machining process, verifying toolpaths through trajectories or machine models. Although custom robotic models like the ASEA robot are not directly supported in these environments, the tools allow the export of machining programs in standardized formats such as APT (Automatically Programmed Tool) files, which represent toolpath geometries and machining commands.

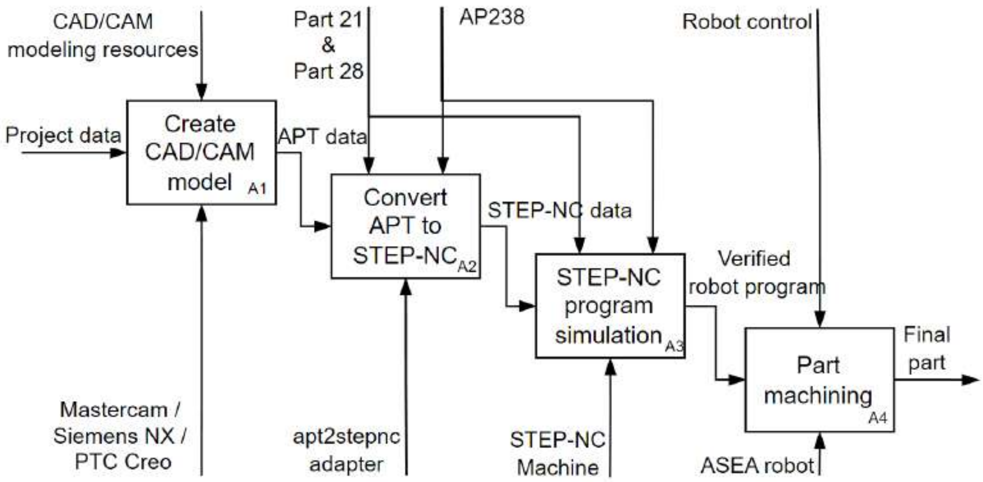


Figure 7.1: IDEF0 activities diagram for the scenario 1.

The APT file generated in the modeling phase is processed in the second activity, where an APT-to-STEP-NC conversion adapter developed in this work translates the APT commands into STEP-NC entities. This adapter, written in C#, utilizes the stepnc.dll library [348] from STEP Tools, Inc., which provides a .NET API for mapping APT commands (e.g., PARTNO, UNITS, CUTTER, RAPID, GOTO, CIRCLE, FEDRAT, COOLNT) to corresponding STEP-NC functions. These mappings allow the creation of a structured STEP-NC object model that explicitly captures all machining parameters. The serialized output is saved in Part 21 or Part 28 (XML) format, ensuring compatibility with simulation and execution environments. Each machining operation in the APT file is linked to a workingstep in the STEP-NC program, complete with its associated toolpath data. The source code of the developed software adapter can be found in its Github repository in [75]. Appendix B includes a comprehensive tutorial on how to configure and use the stepnc.dll in Visual Studio. The tutorial guides the user through the process of creating a simple STEP-NC program, demonstrating the integration of the DLL, setting up the development environment, and utilizing its functions effectively.

The resulting STEP-NC program is then verified in an offline simulation environment using

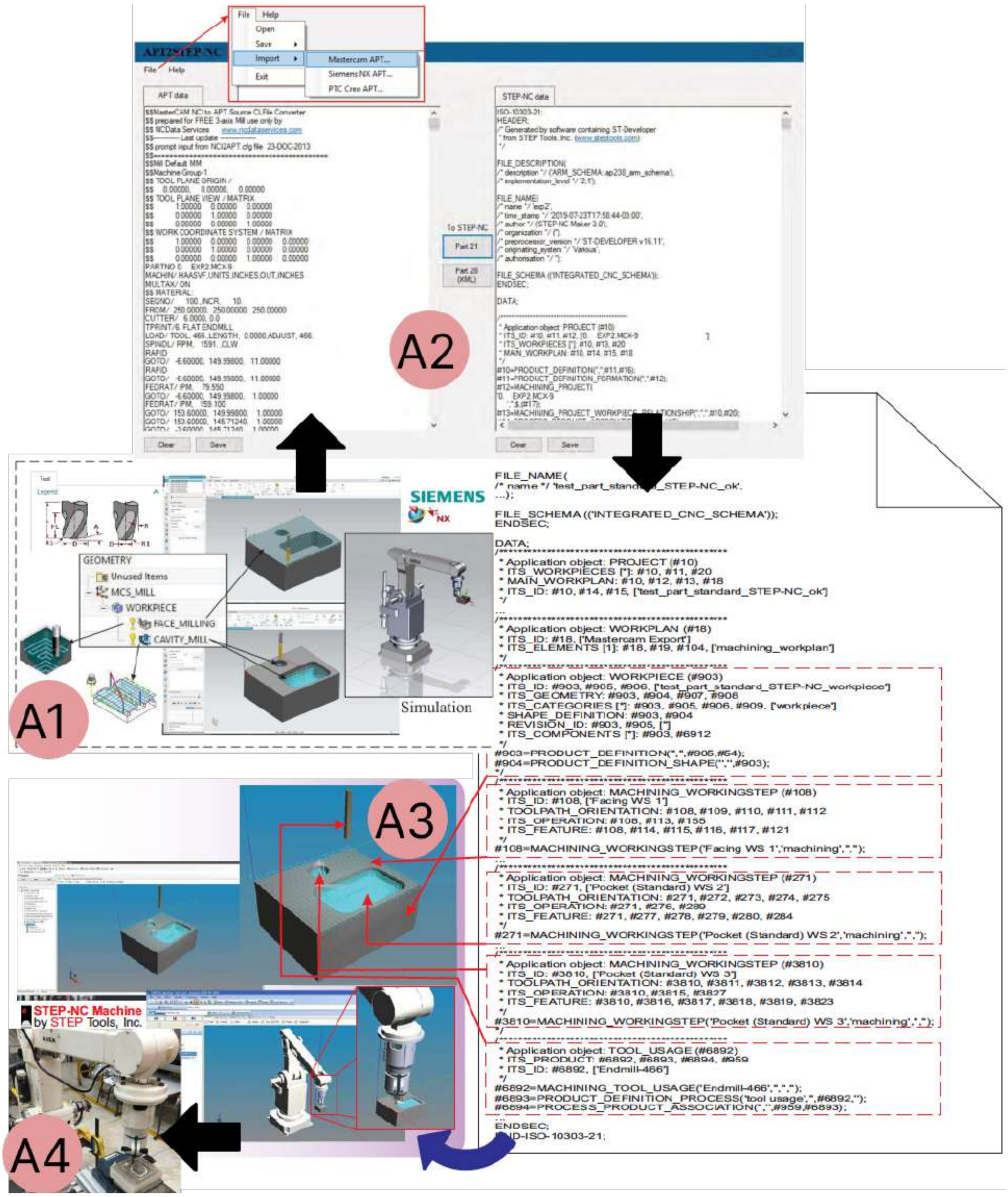


Figure 7.2: Workflow for generating a STEP-NC file from Mastercam machining data using an adapter.

the STEP-NC Machine software. This platform visualizes toolpaths, workpiece geometry, and machining operations while enabling simulation of robotic movements. A kinematic model of the ASEA robot, described through STEP and XML files, is incorporated into the simulation environment. This allows for a detailed examination of the robot's trajectories and ensures that the machining operations conform to the intended specifications.

Finally, the verified STEP-NC program is executed on the physical ASEA robot equipped with a machining spindle and controlled via LinuxCNC. The LinuxCNC controller converts the STEP-NC program into G-code, which guides the robot through the machining process. The manufactured part serves as the tangible output of the integrated workflow, demonstrating the feasibility of using STEP-NC for robotic machining. While this scenario showcases the potential of STEP-NC in advanced manufacturing, it also highlights limitations, such as the indirect execution of STEP-NC programs via G-code. Nonetheless, the approach represents a significant step toward adopting STEP-NC in robotic applications, paving the way for further innovations in fully integrated digital manufacturing ecosystems. This implementation methodology, along with additional approaches, is comprehensively described in the referenced work [324].

The data flow within the DTh for robotic machining, illustrated in Figure 7.3, begins with the design and process planning phases, where the CAD model and machining operations are created using Siemens NX. The machining data, initially exported in APT format, is converted into STEP-NC programs by the adapter software, producing a workplan with workingsteps and detailed machining operations. These STEP-NC programs flow into the simulation phase, where the STEP-NC Machine software uses a kinematic 3D model of the ASEA robot to simulate toolpaths. This phase incorporates the only implemented DTw for this scenario, highlighted with green box in Figure 7.3, which ensures the accuracy and feasibility of the operations. Other DTw are envisioned for future implementation Validated toolpaths then proceed to the manufacturing phase, where the ASEA robot executes them on the real machine equipped with a spindle. This sequence illustrates the seamless flow of data along the proposed DTh for robotic machining, highlighting its interconnected and iterative nature across design, simulation, and manufacturing stages.

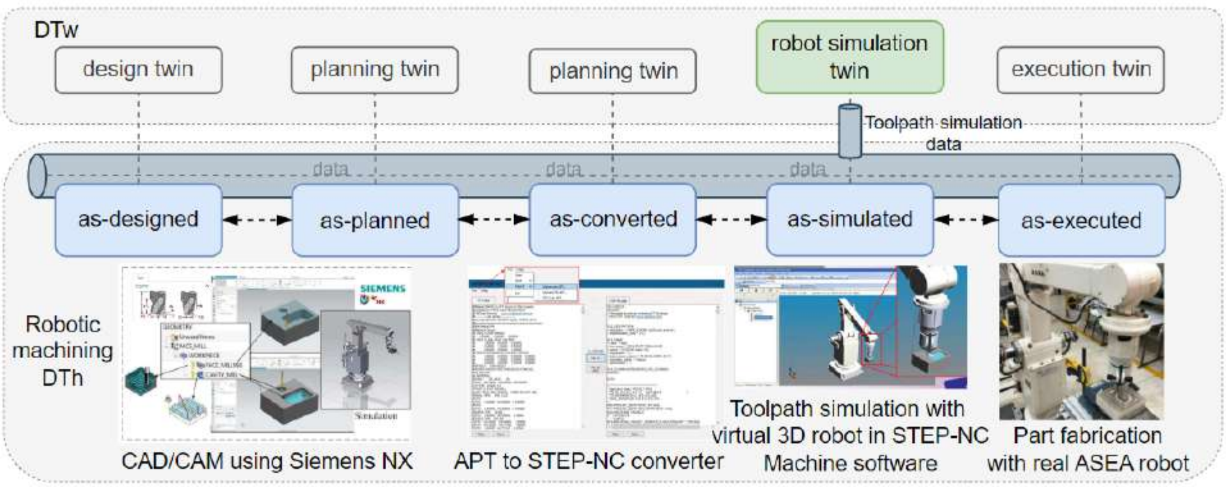


Figure 7.3: Overview of the robotic machining DTh.

7.2 Scenario 2: Implementation of STEP-NC and MTConnect in AM using an FDM process

As outlined in Chapter 5, STEP-NC has seen significant advancements in machining applications since the early 2000s. However, its development for AM processes has lagged behind. It was only in 2020 that Part 17 of ISO 14649 introduced core entities for representing general data definitions in AM within the STEP-NC data model. Despite this progress, the model remains incomplete, lacking support for process parameters tailored to various AM technologies. Moreover, tools like STEP-NC Machine from STEp Tools, in the version available in our laboratory, do not yet support even the foundational entities for AM of Part 17, underscoring the current limitations in practical implementations.

This gap in STEP-NC development motivated the exploration of a novel method in this work, adapting the existing machining model to represent toolpaths for an AM process. Specifically, this implementation scenario focuses on an FDM-based AM process, utilizing the machining-oriented STEP-NC data model to encode the layer-by-layer toolpaths. Additionally, the scenario incorporates an implementation of MTConnect to monitor key process parameters during FDM operations. This system collects real-time data from the machine, including the status of process progress, the temperatures of the print bed and hotend, the X, Y, and Z positions of the machine, and the printing speed, making it accessible for visualization through a web client and providing an effective way to remotely monitor the process.

The digital ecosystem framework proposed in this thesis serves as a reference for structuring the architecture of the implementation scenario, which is detailed in this section. The complete architecture, illustrating the interplay between STEP-NC and MTConnect within of the context of this scenario, is depicted in Figure 7.4. Meanwhile, Figure 7.4 presents the DTh associated with this implementation scenario, outlining the flow of data across a series of phases. In the design phase, the 3D model of the part is created, followed by the planning phase, where the model is sliced into layers, and deposition toolpaths for each layer are generated. These toolpaths are used to create a STEP-NC program containing workingsteps tailored for a FDM AM process. The workingsteps, along with their corresponding deposition toolpaths, are then simulated in the STEP-NC Machine environment, leveraging a kinematic 3D model of the machine to validate the operations. Finally, the part is manufactured on a real 3D printer. The simulation and manufacturing phases feed into DTw for simulation and process monitoring, respectively (highligthed with green boxes in the figure). The simulation DTw ensures toolpath feasibility, while the monitoring DTw tracks key parameters such as process progress, bed and hotend temperatures, the positions of the coordinate axes (X, Y, Z), and the printing speed, providing a comprehensive framework for data-driven oversight of the AM process.

The 3D model of the part to be printed originates from CAD software and is saved in the widely used STL format. This STL file serves as the input for a dedicated AM CAM software,

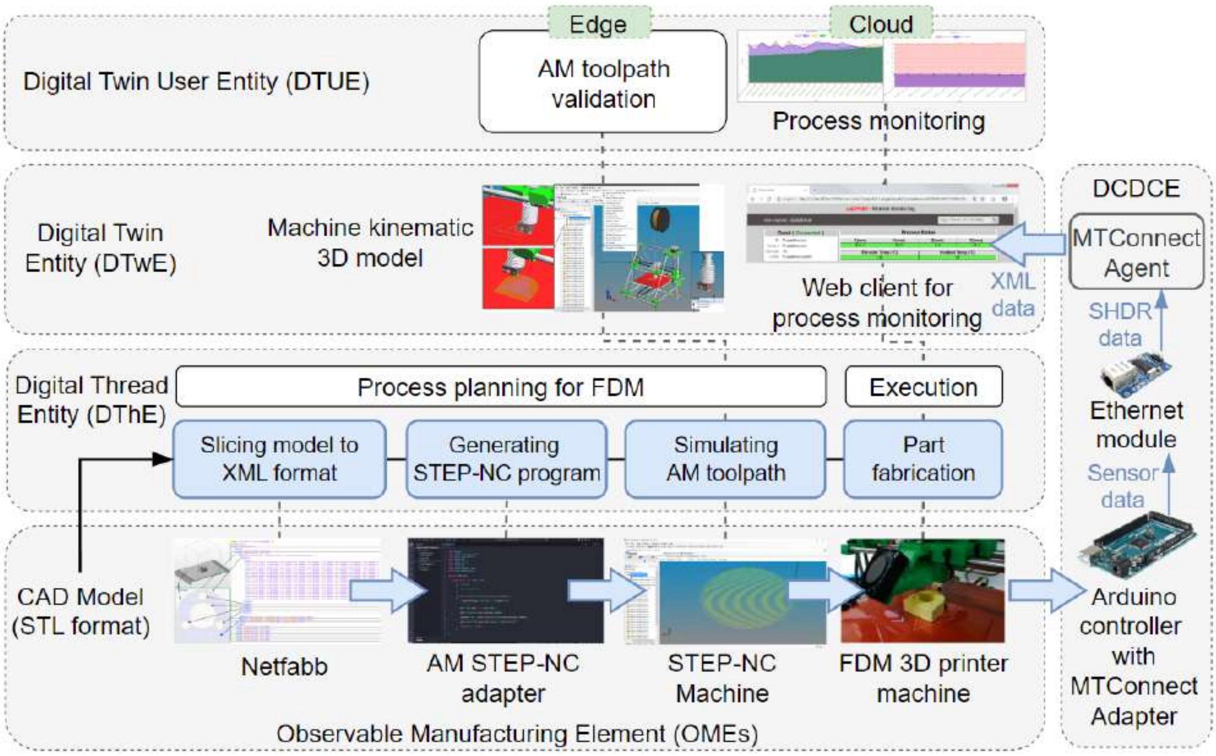


Figure 7.4: STEP-NC and MTConnect implementations in AM through digital ecosystem framework.

Autodesk Netfabb, which is employed in this implementation scenario. Netfabb processes the STL model by slicing it into layers with a specified thickness, defining the FDM process parameters, and generating the corresponding toolpaths for each layer. The toolpaths are then exported in an XML-based AM layer format, encapsulating all necessary data to represent the sliced model.

The structure of the XML file, shown in Figure 7.6, organizes the layer data within the <Layers> tag, which contains multiple <Layer> tags. Each <Layer> tag encapsulates one or more <Exposure> tags, representing individual toolpaths. The type of toolpath, such as contour or hatch, is specified by the "polylineType" property within each <Exposure> tag. Additionally, the <Exposure> tags contain <Segments> blocks, which further subdivide into <Segment> elements. Each <Segment> comprises <Point> tags with attributed x, y, and z properties, defining the coordinates of the polyline points as illustrated in the figure. The XML file, containing comprehensive toolpath data, is then passed to the next stage of the architecture, where it is converted into a STEP-NC program.

The generation of a STEP-NC program for AM represents a key contribution of this method. A dedicated software adapter was developed to process the XML file containing the toolpath data for each sliced layer of the model, parse it, and generate a STEP-NC program tailored for AM. A free version of this software adapter can be found in the Github repository in this reference [76]. This approach adapts the current STEP-NC model, traditionally used for machining, to represent

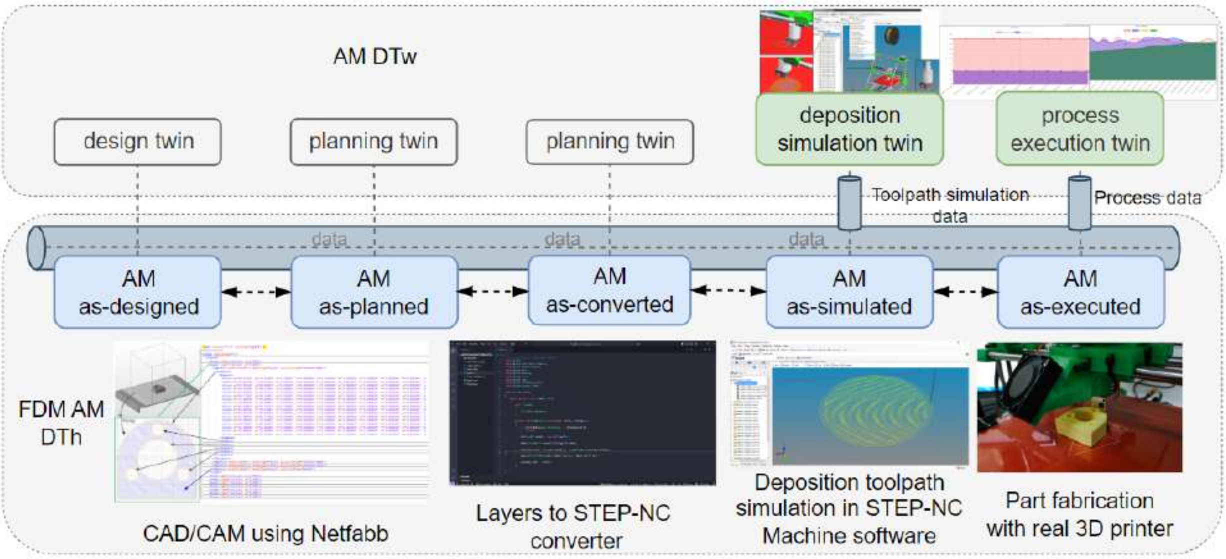


Figure 7.5: Overview of the DTh of the FDM AM process.

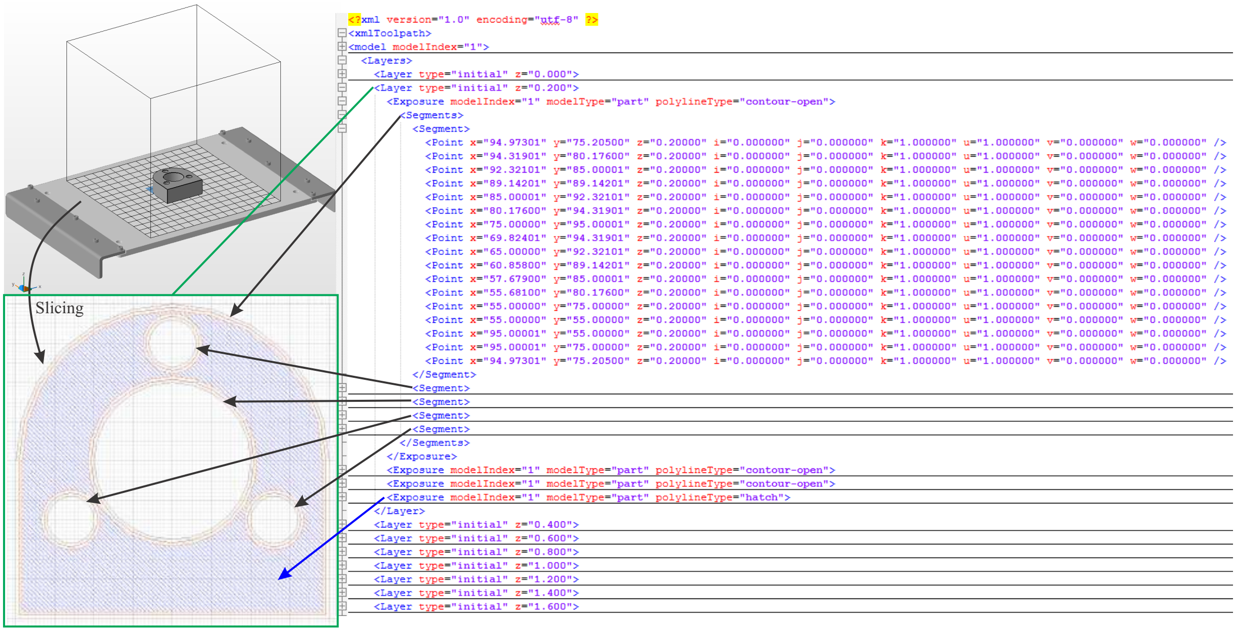


Figure 7.6: Part model sliced into an XML layer file.

toolpaths for an FDM-based AM process. The software adapter leverages the same DLL from the STEP-NC Machine software by STEP Tools Inc., previously utilized in the robotic machining scenario described above. The adapter was developed in C#, integrating the DLL into Visual Studio to access its functionalities.

To incorporate the DLL in Visual Studio, it was added as a reference within the project settings. This step allows the C# application to invoke the library's API, enabling the creation of

STEP-NC models, embedding machining data, and exporting files in either Part 21 or Part 28 formats. The adapter software parses the XML data by creating instances of classes specifically designed to represent the hierarchical structure of layers, exposures, segments, and points defined in the XML file. These instances are stored in memory and subsequently mapped to corresponding STEP-NC definitions.

The generation process begins by initializing a STEP-NC model using the AptStepMaker class constructor from the DLL's API. A new STEP-NC project is then created within this model. Each layer from the XML file is mapped to a STEP-NC workplan belonging to the project, with the workplan's identifier corresponding to the layer number. Within each workplan, every exposure is mapped to a STEP-NC workingstep, representing either a contour or hatch polyline type as specified in the XML file.

The toolpath points from each segment are utilized to define movement commands in the STEP-NC program. This is achieved using the GoToXYZ function from the API, which takes the X, Y, and Z coordinates from the XML structure as input parameters. Other process parameters specific to FDM, such as extruder temperature and feedrate, are mapped to STEP-NC equivalents. The extruder temperature is represented as spindle speed using the SpindleSpeed function, while the feedrate is set using the Feedrate function.

Once all data from the XML has been parsed and integrated into the STEP-NC model, the program is serialized and exported in the Part 21 format. Figure 7.7 illustrates the resulting STEP-NC file, highlighting how contours and hatches are represented within the program. The visualization of the layers in Figure 7.7 is achieved by opening the generated STEP-NC program in the STEP-NC Machine software. This software enables detailed inspection of the toolpaths represented in the program. Specifically, it allows the user to view the contours and hatches of each individual layer, providing a clear representation of how the XML data has been translated into the STEP-NC format. The ability to visualize these details enhances understanding of the slicing and path-planning processes, validating the correct mapping of AM-specific toolpaths within the adapted STEP-NC model. This output demonstrates the feasibility of adapting the STEP-NC machining model to accommodate AM-specific processes, providing a foundational framework for further developments using this approach.

To incorporate a realistic simulation of the 3D printing toolpaths with the actual 3D printer model, the kinematic model of the RepRap 3D printer Prusa Mendel i2 is introduced into the STEP-NC Machine software. This process begins with a STEP file containing the CAD assembly model of the 3D printer, which serves as the basis for generating an associated XML file to define the machine's kinematic structure.

The XML file represents the kinematic model of the AM machine and is structured into two primary sections, "tool" and "workpiece." The "tool" section specifies the geometries and placements associated with the actuated axes that move the tool (e.g., X and Z axes for the Prusa Mendel), while the "workpiece" section details the geometries and placements for components

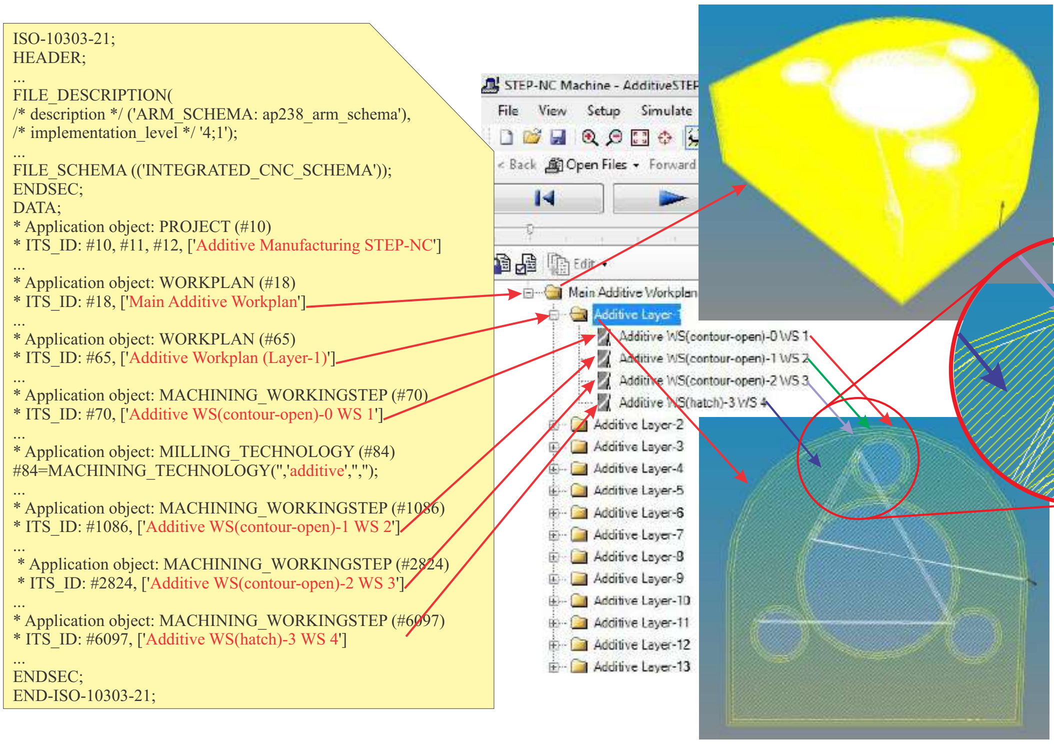


Figure 7.7: AM STEP-NC program and layers visualization in STEP-NC Machine software.

that hold the workpiece (e.g., Y axis). Additional fixed geometries, such as the machine's structure, are defined outside these sections. Optionally, a "changer" section can also be included to describe the tool tree and change positions if the machine supports tool changes. This configuration process is illustrated in Figure 7.8.

The identification of assembly components (`shape_eid`) and faces (`face_eid`) necessary to construct the XML file is achieved using the STEP-NC Machine software's visualization and identification tools. Once the XML kinematic model and STEP assembly file are generated, they are placed in the designated directory within the STEP-NC Machine installation path (typically C:/Program Files (x86)/STEP Tools/STEP-NC Machine/machines). These resources are available in the open Github repository in reference [77].

Within the STEP-NC Machine environment, the kinematic model of the AM machine is loaded for simulation by selecting the relevant machine tool from the "Machine Tool" menu and importing the geometry of the tool (e.g., the 3D printer's hotend) from the "Tool" tab, as shown in Figure 7.9. Similarly, the part's geometry can be included using the "Part Properties" tab. This setup enables a comprehensive simulation that includes the motion of the kinematic model and the toolpath execution, allowing precise verification of manufacturing steps. Alternatively, instead of relying on a separate XML file, the kinematic model can be integrated directly into the STEP document by leveraging the data structures available in the STEP AP-242 standard, which allows for embedding kinematic and geometric relationships.

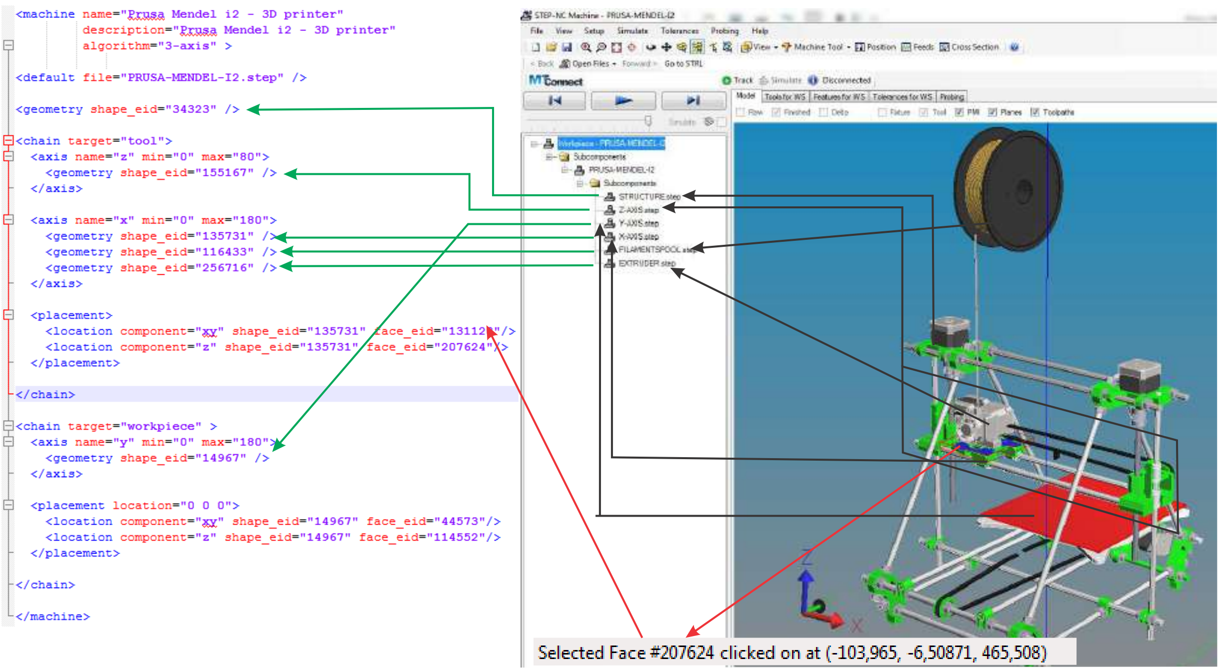


Figure 7.8: Configuring the 3D printer kinematic model into the STEP-NC Machine software.

Beyond toolpath verification, the AP-238 STEP-NC program can be enriched with additional data, such as tool and part geometries, and geometric dimensioning and tolerancing (GD&T) information, leveraging integration capabilities with other STEP resources. This enrichment supports advanced functionalities such as quality checks and the assessment of surface finish requirements, offering opportunities for optimizing manufacturing processes and improving part quality.

From the STEP-NC Machine software, the STEP-NC program can be exported as G-code, which is compatible with the RepRap 3D printer's controller. The printer operates using an Arduino Mega 2560 running the open-source Marlin firmware. However, certain parameters, such as the extruder and print bed temperatures, had to be manually incorporated into the G-code. This adjustment was necessary because the extruder temperature, initially mapped to the spindle speed for machining processes in the STEP-NC program, was not directly translatable. Additionally, the print bed temperature parameter was entirely absent from the STEP-NC program and required manual addition.

This approach highlights both the advantages and limitations of the implemented methodology. On the positive side, it demonstrates the feasibility of adapting the existing machining-oriented STEP-NC model for AM processes, leveraging available tools to generate, simulate, and export programs for a 3D printing workflow. This adaptability showcases the potential of STEP-NC as a foundational standard to bridge gaps between manufacturing technologies. However, significant drawbacks are also evident. The current machining-focused STEP-NC model lacks the comprehensive ability to represent specific AM process parameters, particularly for FDM.

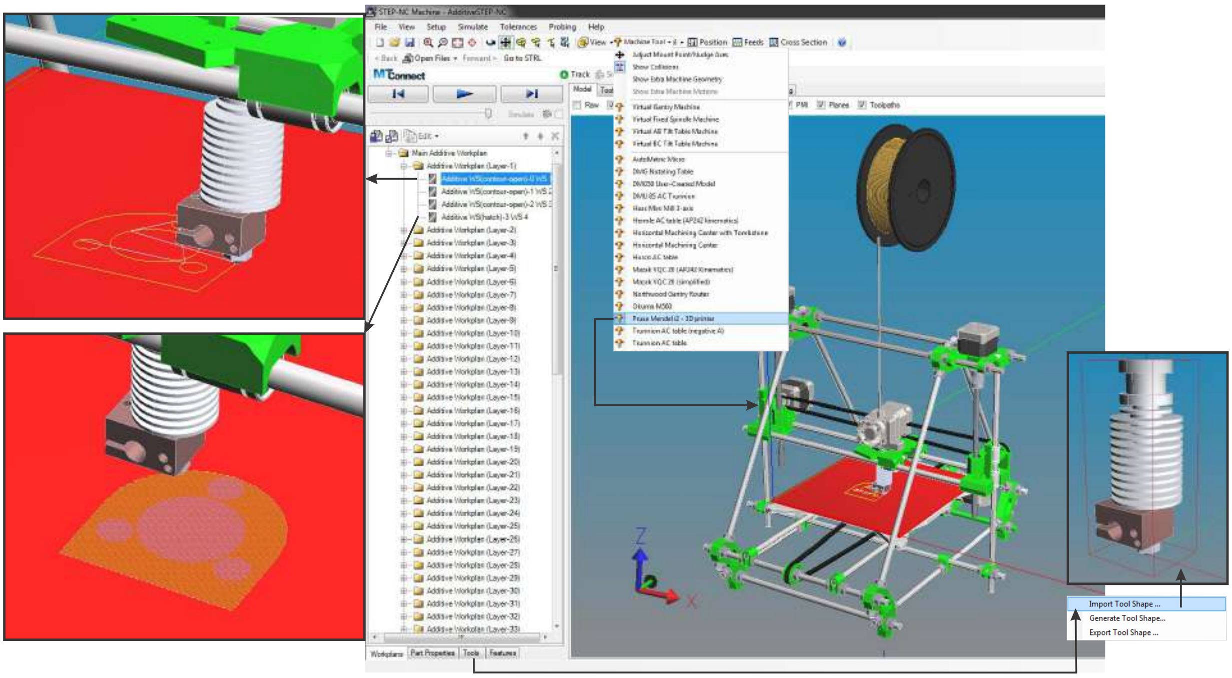


Figure 7.9: Simulation of the AM STEP-NC program with machine 3D model in the STEP-NC machine software.

This limitation necessitated manual interventions, reducing the efficiency and automation potential of the workflow. Moreover, the implementation remains an indirect architecture, as the final execution on the RepRap printer required converting the STEP-NC program into G-code, introducing an additional layer of complexity and potential for errors. These challenges underscore the need for further development of STEP-NC to fully support AM-specific requirements.

As part of the implementation scenario described in this section, the integration of MTConnect was explored to enable real-time monitoring and data collection from the RepRap 3D printer. MTConnect is a widely recognized standard for data exchange and communication in manufacturing environments. Figure 7.10a illustrates the architecture of the MTConnect implementation, which consists of three main components: the adapter, the agent, and the web client. These components work together to establish a seamless data flow from the 3D printer to a cloud-enabled monitoring system.

The experimental setup for this framework is tailored to the Arduino Mega 2560 controller typically used in RepRap machines. To establish a reliable communication channel, an ENC28J60 Ethernet module was connected to the Arduino. This module, compatible with the TCP/IP protocol used by MTConnect, provides a low-cost and efficient means of enabling internet connectivity. A custom software component was developed and embedded into the RepRap's Sprinter firmware. This component collects critical machine data, such as axis positions, hot-end and heatbed temperatures, build progress, and the current layer number. The collected data is formatted as

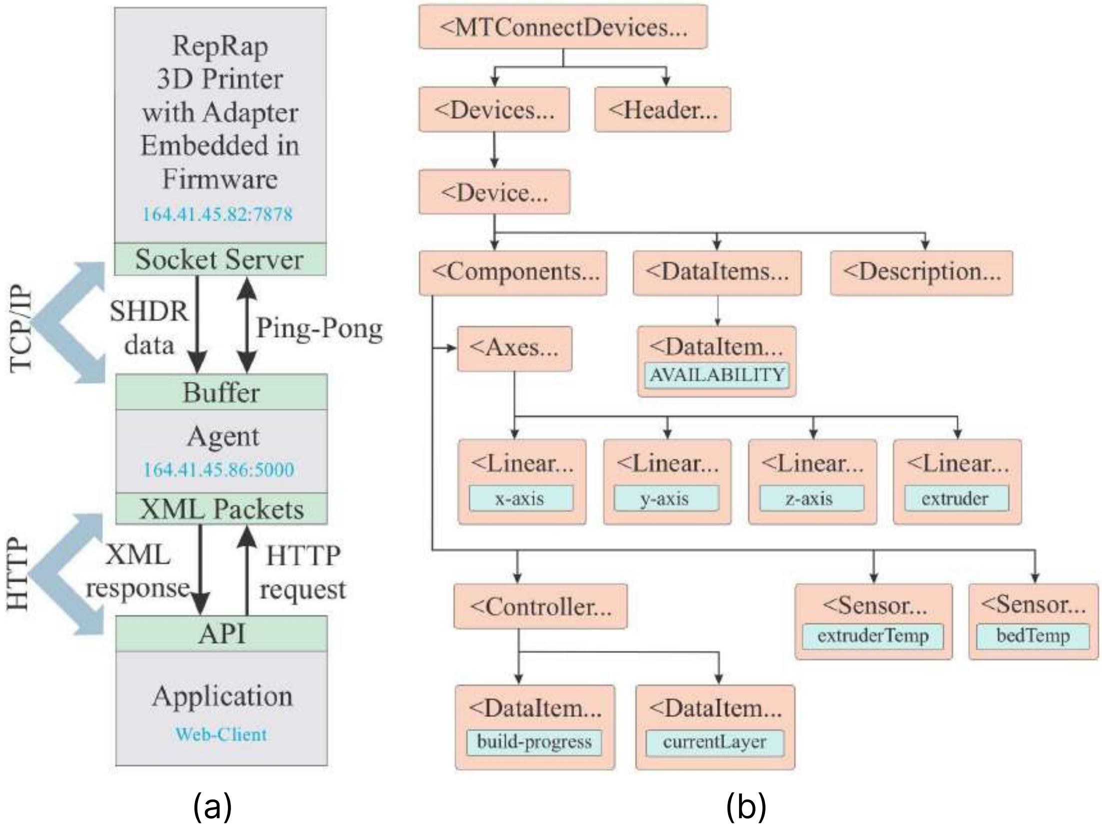


Figure 7.10: MTConnect implementation: a) Architecture; b) 3D printer machine model.

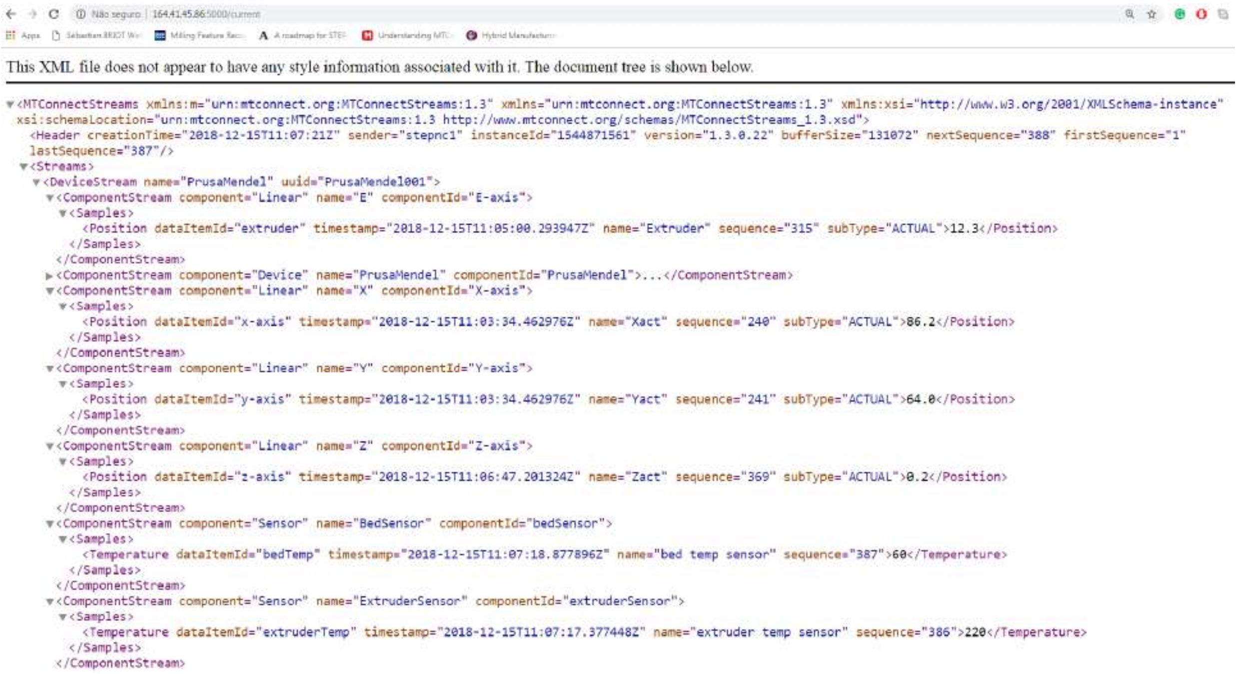
a text dictionary in the Simple Hierarchical Data Representation (SHDR) format and transmitted via TCP/IP.

This approach eliminates the need for external hardware, reducing costs and complexity, while enabling the RepRap machine to integrate seamlessly into a networked manufacturing environment. With this framework, affordable Arduino-based controllers gain extended functionalities to participate in a cloud-enabled manufacturing ecosystem alongside other equipment.

Another critical aspect of this implementation is the creation of the machine information model, depicted in Figure 7.10b. This model follows the unified terminology and structure defined by the MTConnect standard to organize and represent machine data in an XML format. The hierarchical model begins with the structural element MTConnectDevices, which contains sub-elements Devices and Header.

The Devices element includes all the machines in the system, with each machine represented by a Device element. Within each Device, the Description provides metadata about the machine, DataItems lists data attributes such as machine availability, and Components organizes dynamic machine data. For the RepRap 3D printer, these components include positional data for the X, Y, and Z axes, extruder temperature, heat-bed temperature, build progress, and the current layer number. The well-structured XML model ensures compatibility with the MTConnect Agent, facilitating efficient data exchange and real-time monitoring.

Machine data acquisition tests were conducted by making various types of requests directly through a web browser. Figure 7.11 illustrates an XML response to a “current" request, which provides real-time status data from the system. The XML structure adheres to the MTConnect standard, including elements such as axis positions (X, Y, Z), extruder and heat-bed temperatures, build progress, and the current layer number. These standardized XML tags ensure compatibility with MTConnect-compliant client applications, enabling seamless data retrieval and real-time monitoring from a web client.


This XML file does not appear to have any style information associated with it. The document tree is shown below.


```
<MTConnectStreams xmlns:m="urn:mtconnect.org:MTConnectStreams:1.3" xmlns="urn:mtconnect.org:MTConnectStreams:1.3" xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
 xsi:schemaLocation="urn:mtconnect.org:MTConnectStreams:1.3 http://www.mtconnect.org/schemas/MTConnectStreams_1.3.xsd">
  <Header creationTime="2018-12-15T11:07:21Z" sender="stepnc1" instanceId="1544871561" version="1.3.0.22" bufferSize="131072" nextSequence="388" firstSequence="1"
  lastSequence="387"/>
  <Streams>
    <DeviceStream name="PrusaMendel" uuid="PrusaMendel001">
      <ComponentStream component="Linear" name="E" componentId="E-axis">
        <Samples>
          <Position dataItemId="extruder" timestamp="2018-12-15T11:05:00.293947Z" name="Extruder" sequence="315" subType="ACTUAL">12.3</Position>
        </Samples>
      </ComponentStream>
      <ComponentStream component="Device" name="PrusaMendel" componentId="PrusaMendel">...</ComponentStream>
      <ComponentStream component="Linear" name="X" componentId="X-axis">
        <Samples>
          <Position dataItemId="x-axis" timestamp="2018-12-15T11:03:34.462976Z" name="Xact" sequence="240" subType="ACTUAL">86.2</Position>
        </Samples>
      </ComponentStream>
      <ComponentStream component="Linear" name="Y" componentId="Y-axis">
        <Samples>
          <Position dataItemId="y-axis" timestamp="2018-12-15T11:03:34.462976Z" name="Yact" sequence="241" subType="ACTUAL">64.0</Position>
        </Samples>
      </ComponentStream>
      <ComponentStream component="Linear" name="Z" componentId="Z-axis">
        <Samples>
          <Position dataItemId="z-axis" timestamp="2018-12-15T11:06:47.201324Z" name="Zact" sequence="369" subType="ACTUAL">0.2</Position>
        </Samples>
      </ComponentStream>
      <ComponentStream component="Sensor" name="BedSensor" componentId="bedSensor">
        <Samples>
          <Temperature dataItemId="bedTemp" timestamp="2018-12-15T11:07:18.877896Z" name="bed temp sensor" sequence="387">60</Temperature>
        </Samples>
      </ComponentStream>
      <ComponentStream component="Sensor" name="ExtruderSensor" componentId="extruderSensor">
        <Samples>
          <Temperature dataItemId="extruderTemp" timestamp="2018-12-15T11:07:17.377448Z" name="extruder temp sensor" sequence="386">220</Temperature>
        </Samples>
      </ComponentStream>
```


Figure 7.11: MTConnect XML response for “current" request with machine operating.

To evaluate the effectiveness of real-time data access and monitoring, a simple web client application was developed using HTML, CSS, and JavaScript. Figure 7.12(a) showcases a snapshot of its frontend user interface, which can accessed online on the url `https://efrainrodriguez.github.io/MTConnect-client/`. The web client dynamically retrieves and processes XML data from the MTConnect agent in response to a “current" request, displaying essential machine parameters such as axis positions, temperature, build progress, and the current layer. This intuitive interface allows operators to track the machine's operational status during the printing process, providing a user-friendly view of critical metrics. The system was further tested for connectivity and performance. These evaluations verified the agent's ability to communicate with various web-based clients via a browser.

Figure 7.12 presents key reports on monitored data from the RepRap machine in operation. Positional data for the X, Y, Z axes and extruder, shown in Figure 7.12(b), are crucial for ensuring toolpath accuracy. The temperature data for the hot-end and heat-bed, illustrated in Figure 7.12(c),

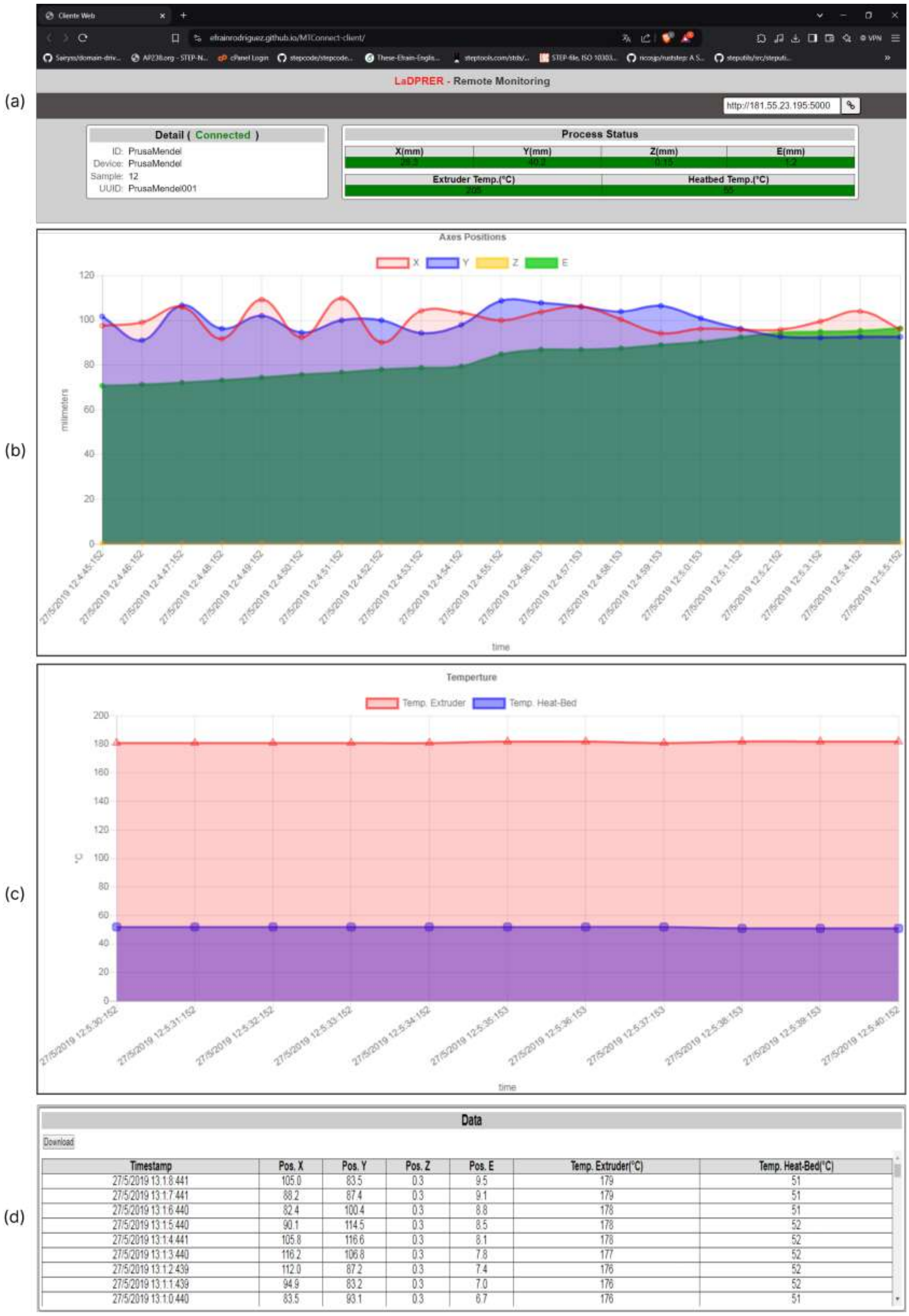


Figure 7.12: MTConnect web client for AM process monitoring.

reflect the controlled conditions necessary for reliable extrusion and layer adhesion. Additionally, Figure 7.12(d) provides a spreadsheet view of historical data stored for all monitored parameters, supporting post-process analysis and quality assessment.

Performance evaluations demonstrated the system's reliability, with a maximum observed delay of approximately 700 milliseconds on a TCP/IP connection with 10 Mbit/s bandwidth. This delay, associated with monitoring eight process variables, is well within acceptable limits for remote supervision applications in 3D printing processes. The observed latency can be attributed to several factors: the inherent overhead of HTTP requests used for data retrieval, the processing time required by the MTConnect adapter to collect and format data in SHDR , and the buffering performed by the agent to manage real-time data streaming.

Additionally, network transmission delay, influenced by bandwidth and packet routing efficiency, contributes to this overall latency. On the client side, the delay is also affected by the speed of rendering XML data into the web-based application. Despite these minimal delays, the system effectively achieves near real-time data retrieval, making it suitable for monitoring and supervising AM operations.

7.3 Scenario 3: Simulation of the STEP-NC program for the robotic LMD process

The simulation of STEP-NC programs for the LMD process using the Kuka KR70-2100 robot demonstrates the adaptability of STEP-NC for metal AM. This scenario emphasizes the integration of AM toolpaths with robotic systems and the importance of realistic simulation for verifying toolpaths in 3D metal printing. Figure 7.13 illustrates the 3D kinematic model of the Kuka KR70-2100 robot integrated within the STEP-NC Machine environment. The simulation showcases the toolpath for a cylindrical part geometry, with the robot's movements following the generated trajectories.

The process begins with a 3D part model in STL format, which is sliced in Autodesk Netfabb to generate toolpaths. These toolpaths are exported in an XML-based layer format and converted into a STEP-NC program using the software adapter developed in C#. This adapter maps the sliced layer data into STEP-NC entities, translating deposition paths into Workingsteps.

To enable simulation, the kinematic model of the Kuka KR70-2100 robot is incorporated into the STEP-NC Machine environment. This involves creating a kinematic configuration XML and integrating it with the robot's 3D model. The resulting setup allows for visualizing the robot's execution of the LMD toolpaths, validating both the toolpath accuracy and the robot's kinematic constraints.

This implementation highlights the potential of STEP-NC to support LMD process operations while identifying significant gaps in the standard for fully representing LMD-specific parameters. Currently, the lack of dedicated entities to define essential LMD process data—such

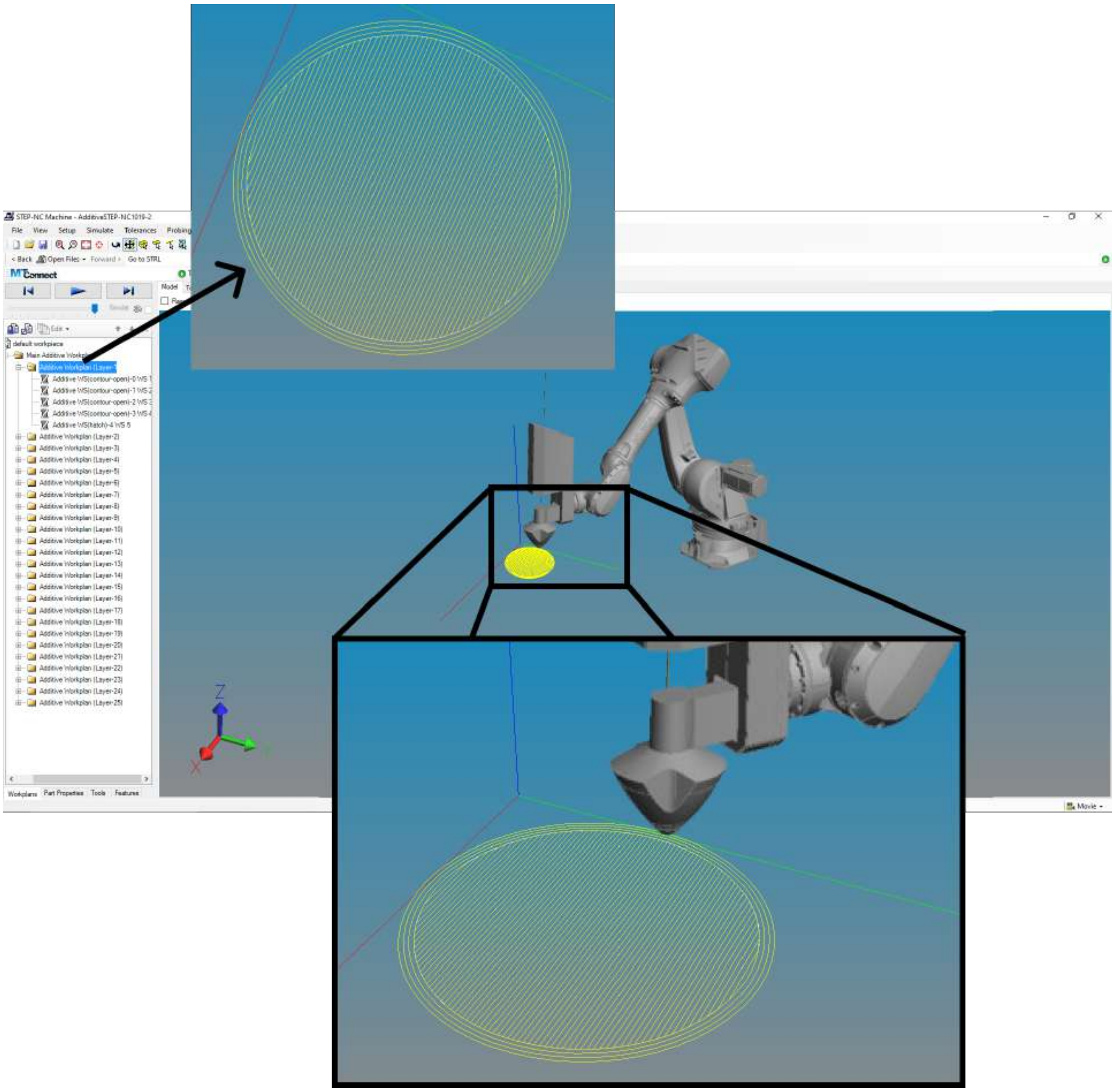


Figure 7.13: STEP-NC toolpath simulation for LMD process.

as laser power, powder flow rate, or shield gas parameters—limits the ability to natively include such information within the STEP-NC program. As a result, these parameters cannot be directly represented or simulated, reducing the comprehensiveness of the DTh for LMD processes.

Additionally, the conversion of the STEP-NC program into KUKA Robot Language (KRL)—the proprietary programming language for Kuka robots—is necessary for execution. While the STEP-NC program provides a high-level, interoperable representation, the translation to KRL is essential to enable real-world operation. To ensure that toolpaths are correctly interpreted and executed by the robot, subsequent simulation within the KUKA Sim environment is recomended. This simulation step validates the converted toolpaths, ensuring compatibility and precision before deployment in the physical system.

It is important to note that this implementation focused solely on the simulation of the STEP-NC program with the kinematic model of the Kuka KR70-2100 robot and the LMD printhead developed by Meltio. No physical execution was performed, further underscoring the necessity of simulation as a critical step in bridging digital and physical operations. The findings of this work highlight the pressing need to extend the STEP-NC standard with entities specifically designed to support LMD processes, enabling a more integrated and robust representation of metal AM within the digital ecosystem.

Figure 7.14 illustrates the DTh for this implementation scenario. The process begins with the creation of a STEP-NC program defining workingsteps and deposition toolpaths for LMD operations. These toolpaths are simulated in the STEP-NC Machine environment using a kinematic 3D model of the KUKA KR70 robotic arm. At the core of this simulation phase is the DTw of the KUKA KR70 (highlighted with the green box in th figure), providing real-time feedback to validate and refine toolpaths in a virtual environment before physical execution. By integrating the STEP-NC program and the simulation DTw, this DTh optimizes the deposition process while reducing risks and ensuring precision in manufacturing.

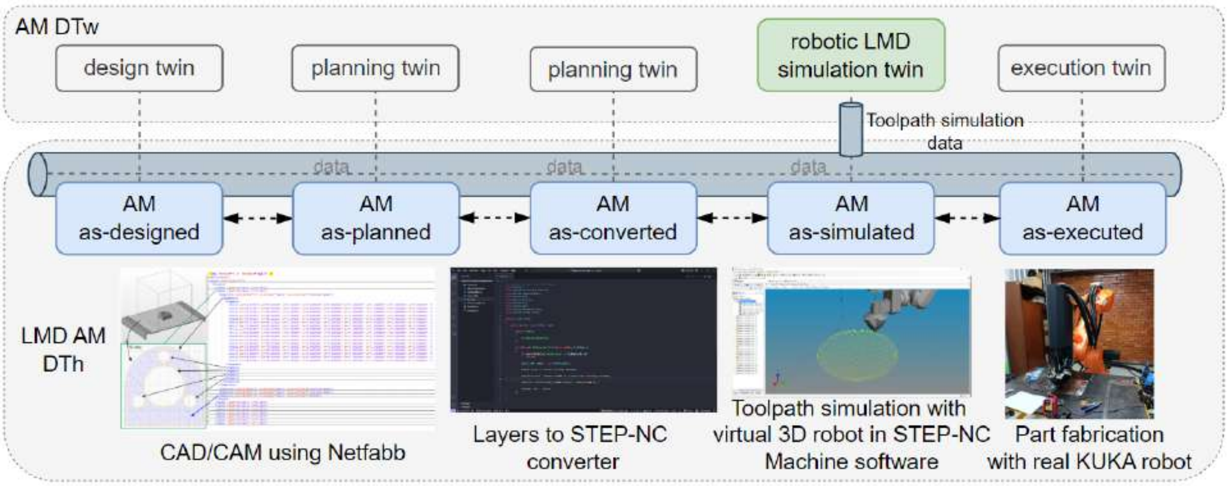


Figure 7.14: Overview of the DTh of the LMD AM process.

7.4 Scenario 4: EXPRESS modeling of STEP-NC data entities for FDM and LMD processes

The limitations observed in the implementation scenarios described earlier, where the current STEP-NC data model for machining was adapted to represent AM processes, highlight the necessity of proposing a new data model for specific AM technologies. While these adaptations successfully demonstrated the feasibility of using STEP-NC for AM, they also exposed significant gaps in the ability of the existing model to fully address the unique requirements of AM processes, such as FDM and LMD. Key limitations include the inability to natively represent critical AM process parameters, such as extrusion temperature, layer height, or deposition rates, and the lack of entities designed to handle the layered, iterative nature of AM toolpaths. This section introduces a novel EXPRESS-based data model for STEP-NC, specifically designed to accommodate the distinct characteristics and requirements of the FDM and LMD processes, addressing these shortcomings and enabling a more seamless integration of AM within the proposed digital ecosystem.

The significance of FDM and LMD processes cannot be overstated in the landscape of modern manufacturing. FDM has exploded in popularity because of its accessibility, versatility, and user-friendly nature, making it a preferred choice for prototyping and small-scale production across various industries. On the other hand, wire-based LMD provides innovative solutions for metal fabrication, unlocking new opportunities for advanced industrial manufacturing applications.

Currently, our laboratory is equipped with several FDM machines, including both RepRap-based and custom-built models. Recently, we have also integrated a Meltio wire-based LMD head into a Kuka KR70 2100 industrial robot. The ongoing lab projects are focused on developing DTws for these systems, with the goal of optimizing process parameters and improving operational efficiency [349, 350]. The current AM STEP-NC model in Part 17 of ISO 14649, which is part of AP238, does not include entities related to the unique aspects of these AM processes. To address this gap, we propose the following STEP-NC entities for FDM and wire-based LMD, constructed using the EXPRESS language. Specifically, we define five primary entities that encompass the essential components of these technologies: `am_deposition_operation`, `am_fdm_technology`, `am_lmd_technology`, `am_fdm_machine_functions`, and `am_lmd_machine_functions`.

The entity `am_deposition_operation`, presented in Figure 7.15, defines a general type of operation for AM processes where material is deposited layer by layer, such as in FDM and LMD. This is a subentity of `am_twod_operation`, which in turn extends from the `am_operation` entity, defined in Part 17 as a type of manufacturing operation. In addition to inheriting properties from `am_twod_operation`, the `am_deposition_operation` includes several critical parameters: `perimeters`, which indicates the number of perimeters that define the thickness of the shell of the layer; `minimum_shell_thickness`, which specifies the minimum allowable thickness for the shell of the layer; `external_perimeters_first`, a boolean value that determines whether external perimeters should be printed before internal ones; `seam_position`, which defines the position of the seam in the layer, and can be one of the following options: `random`, `nearest`, `aligned`, or `rear`; `infill_percentage`, representing the percentage of infill material within the layer, affecting the density and strength of the final part; `infill_pattern`, which specifies the pattern used for infill, with options including `rectilinear`, `grid`, `triangles`, `stars`, `honeycomb`, `cubic`, `concentric`, and `gyroid`; `infill_before_perimeters`, a boolean parameter that indicates whether the infill should be printed before the perimeters; `skirt_loops`, the number of loops to be created for the skirt, which is an initial perimeter that helps prime the extruder before printing the actual part; `skirt_distance`, the distance from the part to the skirt, allowing for some separation between them; `interior_brim_width`, which specifies the width of the brim on the interior side of the part, aiding in adhesion during the print; and `exterior_brim_width`, which indicates the width of the brim on the exterior side of the part, similarly enhancing adhesion.

These properties collectively facilitate precise control over the deposition process and their careful adjustment is crucial for achieving high-quality depositions with optimal mechanical properties.

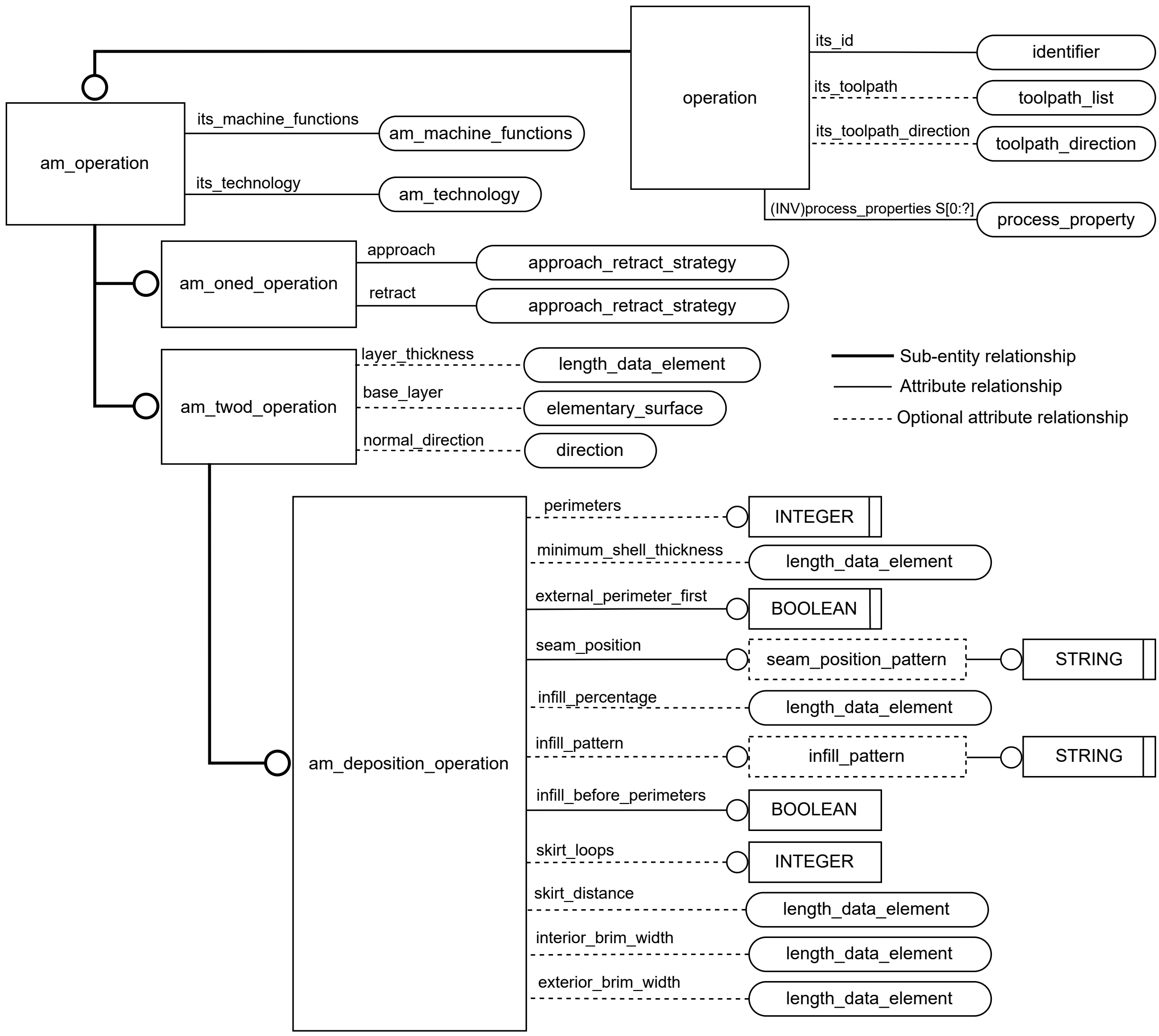


Figure 7.15: EXPRESS-G diagram of the proposed am_deposition_operation entity.

The `am_fdm_technology` entity extends from the `am_technology` entity and aims to relate parameters specific to the FDM technology through several properties, as shown in 7.16. Key parameters include nozzle_diameter, which indicates the diameter of the nozzle used for material extrusion; nozzle_area, representing the cross-sectional area of the nozzle, affecting the flow rate of the material; and extruder_type, which can be classified as either direct or bowden, determining the mechanism used to feed filament into the nozzle. Other significant properties include small_perimeter_speed, which defines the printing speed for small perimeters, external_perimeter_speed, indicating the speed for external perimeter printing, travel_speed, the speed at which the print head moves when not extruding material, and extrusion_speed, which specifies the speed at which material is extruded through the nozzle during printing. Additionally, the am_fdm_technology entity can be extended to represent specific types of FDM technologies, such as am_filament_based_fdm_technology and am_paste_based_fdm_technology. The am_filament_based_fdm_technology entity encompasses properties like filament_diameter, which denotes the diameter of the filament used for printing; retract_extrusion, a boolean value that indicates whether retraction of filament should occur during non-printing movements; and retract_extrusion _length, which specifies the length of filament retracted to prevent oozing during travel moves. The extension to am_paste_based_fdm_technology allows for parameters related to paste extrusion processes, optimizing the technology for applications like food printing or ceramics. Collectively, these properties and entities ensure precise control over the FDM process, enabling high-quality and tailored prints based on specific material and technology requirements.

The am_lmd_technology entity extends from the am_ded_technology entity (Figure 7.17), which in turn extends from am_technology, representing the DED technology. This entity encompasses parameters such as small_perimeter_speed, indicating the speed for printing small perimeters; external_perimeter_speed, specifying the speed for external perimeter operations; travel_speed, the speed at which the deposition head moves when not depositing material; deposition_speed, defining the speed of material deposition during the operation; substrate_thickness, which refers to the thickness of the substrate on which the material is deposited; and substrate_surface, describing the surface characteristics of the substrate. The am_lmd_technology entity inherits these properties and adds further specifications, including laser_power, indicating the power output of the laser used for deposition; laser_beam_diameter, which denotes the diameter of the laser beam; laser_beam_profile, which can be one of gaussian, flat-top, or bessel, affecting the distribution of energy; and laser_focus, describing the focal point of the laser beam during operation. Additionally, the am_lmd_technology entity can be extended to represent specific LMD technologies, such as am_wire_based_lmd_technology and am_powder_based_lmd_technology. The am_wire_based_lmd_technology entity can relate parameters including wire_diameter, denoting the diameter of the wire used; wire_feedrate, which indicates the rate at which the wire is fed into the deposition process; and stand_off_distance, referring to the distance between the wire and the substrate dur-

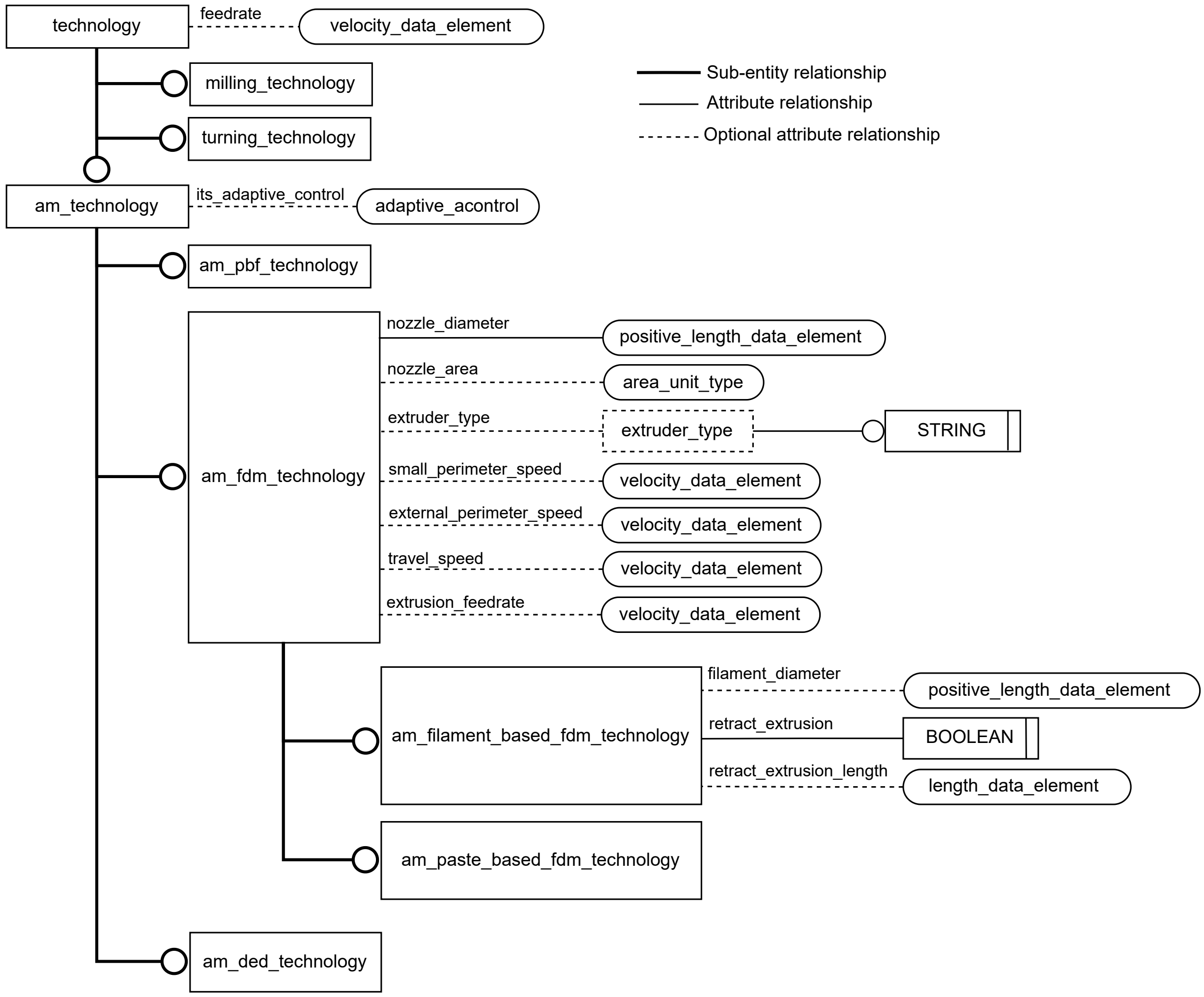


Figure 7.16: EXPRESS-G diagram of the proposed am_fdm_technology entity.

ing deposition. Conversely, the `am_powder_based_lmd_technology` entity focuses on parameters such as `particle_diameter`, which specifies the size of the powder particles, and `powder_feedrate`, indicating the rate of powder feed into the deposition area. Furthermore, processes utilizing wire-arc AM can also be encompassed within the `am_ded_technology` through the `am_wire_arc_technology` entity, expanding the versatility and applicability of the DED approach in AM.

The `am_machine_functions` entity (in Figure 7.18) encompasses the essential machine functions in AM, providing a framework to describe various operational parameters critical to the functioning of AM equipment. This entity may include optional properties to relate data such as `chamber_temperature`, indicating the temperature within the build chamber; `chamber_pressure`, which specifies the pressure inside the chamber; and `chamber_humidity`, representing the humidity level in the build environment. The `am_machine_functions` entity extends to include `am_fdm_machine_functions` and `am_ded_machine_functions`.

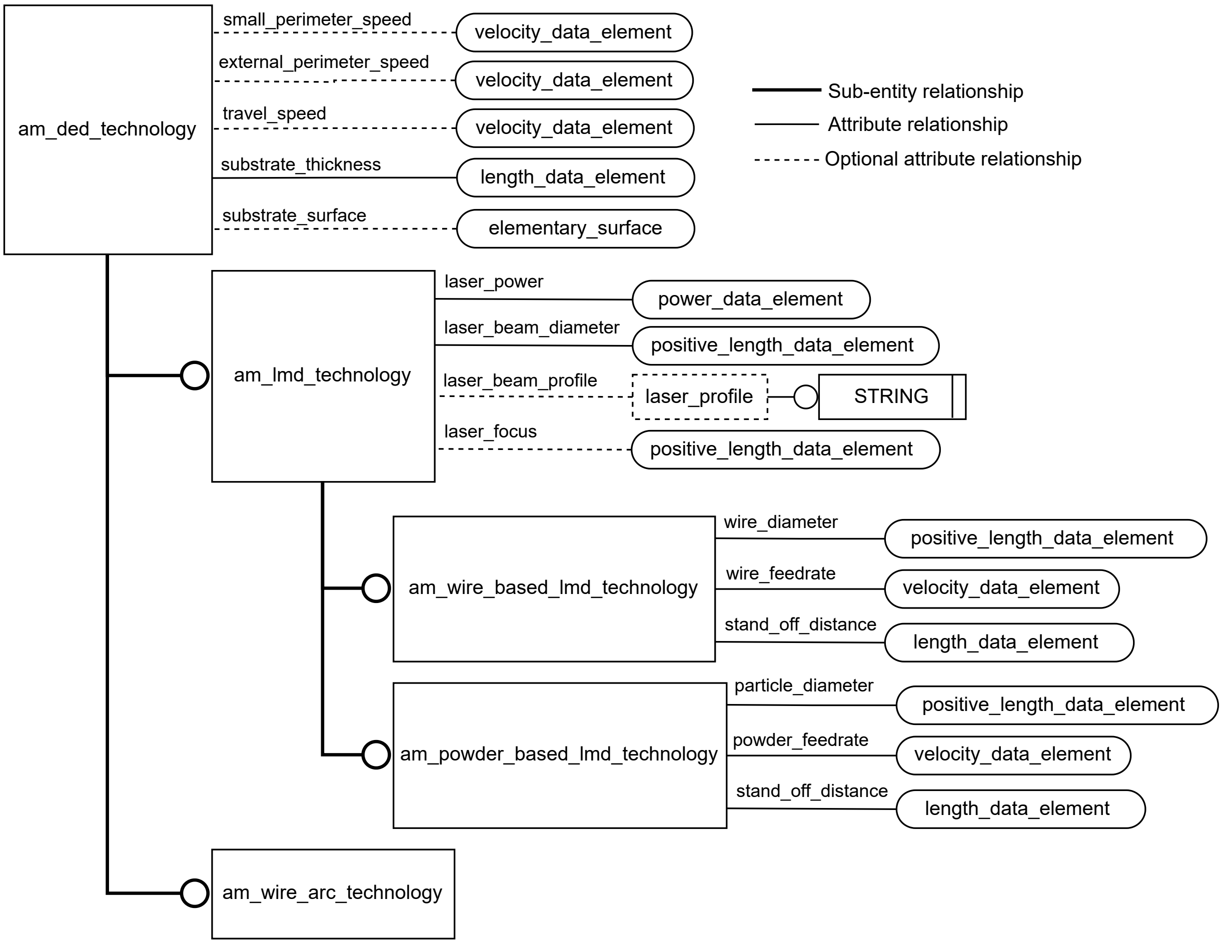


Figure 7.17: EXPRESS-G diagram of the proposed am_lmd_technology entity.

The `am_fdm_machine_functions` entity focuses on parameters specific to FDM technologies, relating data such as `extruder_temperature`, which defines the temperature of the extruder during material deposition; `build_plate_temperature`, indicating the temperature of the build plate to enhance adhesion; `extruders`, representing the number of extruders available; `active_extruder`, denoting which extruder is currently in use; `wipe_while_retracting`, a Boolean property that specifies whether the extruder should wipe off material while retracting; `extruder_offset`, which refers to the positional offset of the extruder; `build_plate_offset`, indicating the offset of the build plate; `auto_cooling`, a feature that enables automatic cooling of the extruder after use; `cooling_speed`, which determines the rate at which cooling occurs; and `keep_fans_always_on`, a property that indicates if the fans should remain continuously operational to manage temperatures effectively.

Conversely, the `am_ded_machine_functions` entity pertains to DED technologies and can relate parameters such as `gas_shield`, which describes the type of gas shield used during the deposition process; `gas_flow_shield`, specifying the flow rate of the shielding gas; and `its_cooling_method`, detailing the method employed for cooling the system. This entity

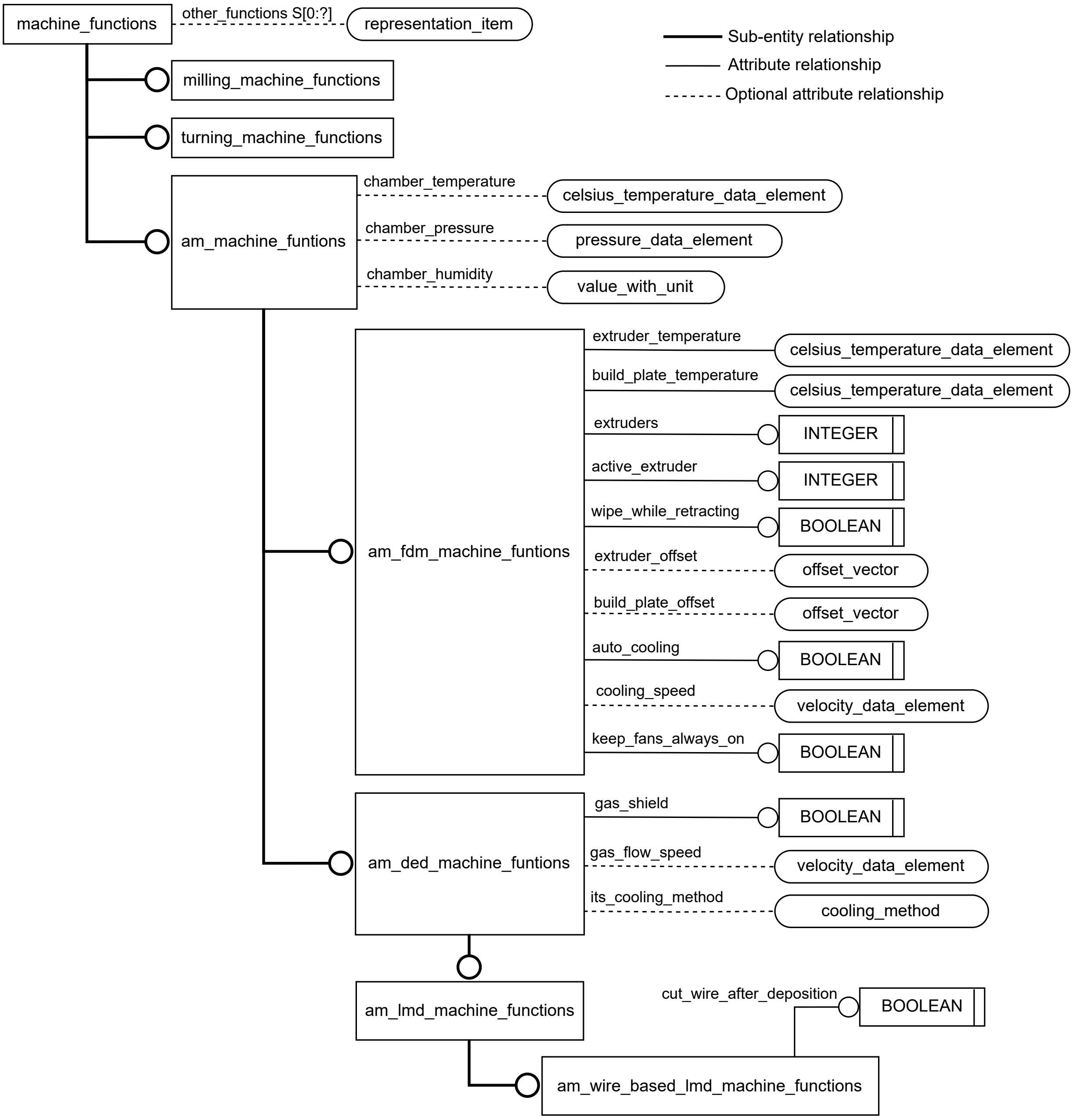


Figure 7.18: EXPRESS-G diagram of the proposed am_machine_functions entity.

further extends to `am_lmd_machine_functions` and `am_wire_based_lmd_machine_functions`. The `am_wire_based_lmd_machine_functions` entity adds the property `cut_wire_after_deposition`, which indicates whether the wire should be cut after the deposition process is completed.

The proposed models must be validated through real-world implementation in manufacturing environments. However, these models provide a foundational base for defining additional parameters within the STEP-NC model for FDM and LMD processes.

7.5 Scenario 5: Development of a new software library to handle STEP-NC programs

One of the main challenges in working with STEP and STEP-NC lies in the scarcity of tools available for developing and implementing STEP-NC models and generating corresponding programs. The inherent complexity of STEP-NC also serves as a barrier, requiring advanced software engineering knowledge and significant programming resources for tool development. Furthermore, this lack of tools significantly limits research and innovation in the field, as investigators and developers face substantial hurdles due to the absence of accessible, modern solutions.

Current available tools are either prohibitively expensive or outdated. For example, STEP Tools Inc. provides one of the few comprehensive solutions for STEP-NC, including the STEP-NC Machine software and the ST-Developer suite. However, these tools are costly, and many institutions or laboratories, including ours, only have access to older versions like the 2010 edition, which lacks support for newer entities. Moreover, these closed solutions do not allow for the inclusion of new entities in their STEP-NC models. On the other hand, JSDAI (Java Standard Data Access Interface) [351] was developed as an early framework for working with STEP models. It provides tools to parse EXPRESS schemas, generate Java classes, and interact with STEP data. However, JSDAI is an outdated solution, designed in the 1990s, and is no longer maintained or supported. Although it allows for generating new entities and working with STEP-NC data, its technology is cumbersome, relying on legacy Java versions that make modern runtime environments difficult to implement.

Given these challenges, a new library is proposed to address the need for accessible and modern tools for working with STEP-NC. This library must meet several critical requirements, as outlined in Table 7.1.

Table 7.1: Key requirements for the proposed STEP-NC library

Requirement	**Justification**
Open Source	Ensures accessibility for researchers and developers, fostering collaboration and innovation.
Modern Technology	Ensures compatibility with current software development practices and integration with existing systems.
Extensibility	Allows the inclusion of new entity classes and schemas, enabling adaptation to evolving needs.
Basic STEP-NC Functionality	Supports reading and writing of Part 21 files, which are fundamental for any STEP-NC implementation.
Web-Oriented	Facilitates cross-platform accessibility and usability in web-based applications and environments.

A key step in constructing a library is selecting the programming language in which it will be developed, as this decision directly impacts its functionality, adaptability, and accessibility. TypeScript is chosen as the development language for the proposed STEP-NC library due to its alignment with the outlined requirements.

TypeScript, a language based on JavaScript, extends its capabilities by supporting static typing and object-oriented programming. This combination makes TypeScript a versatile language suitable for developing a wide range of applications, from web-based tools to server-side systems. Its growing popularity has positioned it as one of the most widely used languages today, both within the open-source community and across industry sectors. Furthermore, TypeScript benefits from the robust ecosystem of Node.js, which serves as its runtime environment. Node.js provides access to one of the largest repositories of libraries in the world, npm (Node Package Manager), enabling developers to integrate diverse functionalities from thousands of open libraries available.

To meet the outlined requirements, the first step is to make the library openly available to the community, ensuring accessibility and collaboration. An open-source approach not only allows the library to be widely adopted but also fosters collective contributions, enhancing its capabilities. To achieve this, the library is hosted in a public repository [352], offering unrestricted access to its codebase, and is also published as an npm package [80]. This ensures that anyone can easily download, use, and contribute to the library, creating a collaborative environment for continuous improvement and innovation.

The proposed STEP-NC library is built and maintained using a cutting-edge technology stack, addressing the requirement for modern technology. Figure 7.19 illustrates the core tools supporting its development, including NX, ESLint, Prettier, Jest, and Verdaccio. NX enables modular development through a monorepo structure, enhancing scalability and efficient dependency management. ESLint and Prettier ensure high code quality and consistent formatting, streamlining collaboration and minimizing potential errors. Jest provides comprehensive testing capabilities, ensuring the library's reliability across various use cases. Verdaccio acts as a private npm repository, enabling secure internal testing and versioning before public releases. Together, these tools fulfill the requirements for a robust, modern, and extensible STEP-NC library while laying a strong foundation for future enhancements.

To meet the requirement of extensibility, the library leverages the principles of object-oriented programming (OOP), including inheritance, abstraction, composition, and aggregation. These principles allow the library to be modular and adaptable, enabling the addition of new entities or schemas as needed without disrupting the existing structure. Meanwhile, the schemas package contains all the entities grouped by schemas, each schema corresponding to a specific application domain.

The general structure of the library is illustrated in Figure 7.20, which showcases its organization into two main packages: core and schemas. The core package serves as the foundation, containing base classes that establish the essential hierarchy and structure for representing a STEP

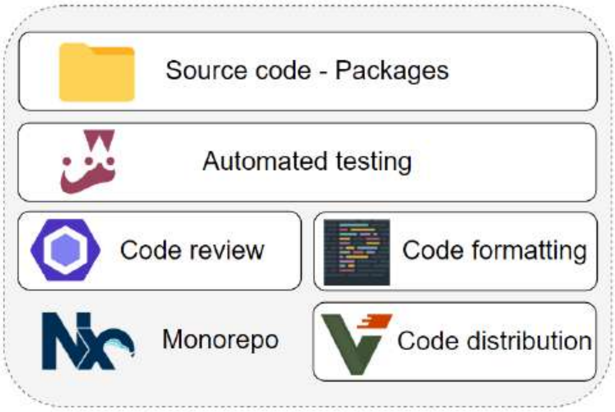


Figure 7.19: Technology stack used to build the STEP-NC library.

or STEP-NC model. These base classes are designed to be highly reusable and extensible, providing a flexible framework for building specialized entities and models.

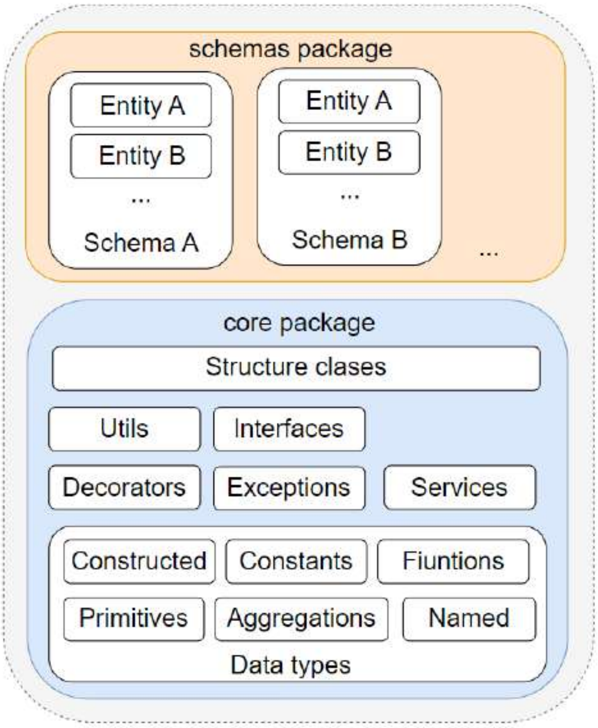


Figure 7.20: Structure of the STEP-NC library.

In alignment with the STEP and STEP-NC standards, EXPRESS defines the modeling language and data structures that form the foundation of these schemas. This includes primitive data types, aggregates, constructed types, named types, constants, and functions, among others. Within the library, these fundamental EXPRESS data types have been mapped to TypeScript classes, each representing a specific data structure. Among the named types, the entity stands out as a core construct that defines domain-specific data elements within a schema, such as those related to design or manufacturing. Entities establish the hierarchies and relationships that form the backbone of a data model.

To support the creation and extension of schemas, an abstract class, EntityBase, has been introduced within the core package of the library. This class defines essential properties and methods that all entities must implement, serving as the base for adding new entities to any schema within the library. Developers extending the library can use this abstract class to ensure consistency and adherence to the framework's standards.

Additionally, a decorator pattern has been employed to manage metadata for each entity class. Two key decorators, Entity and Attribute, are critical for establishing relationships between entities and enabling the serialization and deserialization of class instances during runtime. The Entity decorator is applied to each entity class, facilitating the addition of parent references (if specified) and registering the class in a global map for runtime operations. Meanwhile, the Attribute decorator is applied to each entity property, capturing metadata about the attributes to further support runtime serialization and deserialization.

Figure 7.21 illustrates a code snippet of an entity created using the library, showcasing both the extension of the abstract EntityBase class and the application of the Entity and Attribute decorators. This example highlights the streamlined process developers can follow to introduce new entities, ensuring compatibility and ease of integration within the library's extensible framework.

To meet the requirement of basic functionality for reading and writing STEP-NC files in Part 21 format (P21), the library includes specialized classes within its services folder: P21Writer and P21Reader. These classes are fundamental for enabling serialization of a model into a P21 file and deserialization of a P21 file into a model, thus facilitating the handling of STEP-NC data.

The P21Writer class is designed to serialize an instance of a model, which comprises properties linking instances of classes that represent sections, further containing hierarchies of related entity instances. The class allows developers to create an instance of P21Writer and invoke its write method, specifying the file path where the generated P21 document will be saved. This process leverages the hierarchical relationships within the model to create a structured P21 file. Figure 7.22 illustrates an example of a P21 file generated by P21Writer for a simple entity hierarchy.

Similarly, the P21Reader class enables the deserialization of a P21 file into a corresponding model of related entity instances. By creating an instance of P21Reader, developers can use its parse method, which takes the file path of the P21 document as input. Upon successful parsing, the class constructs a model by instantiating entities and their relationships based on the data extracted from the file.

Both classes utilize the metadata registered by the Entity and Attribute decorators applied to entity classes when included in the library. This metadata is critical for mapping the properties of

```typescript
export interface FileDescriptionProps {
  description: ListType<StringType>;
  implementationLevel: StringType;
}

@Entity()
@Instantiable()
export class FileDescription
  extends EntityType<FileDescriptionProps>
  implements FileDescriptionProps
{
  constructor(props: FileDescriptionProps) {
    super(props);
    this.description = props.description;
    this.implementationLevel = props.implementationLevel;
  }

  @Attribute(genericType(ListType, genericType(StringType)))
  description: ListType<StringType>;

  @Attribute()
  implementationLevel: StringType;
}
```

Figure 7.21: Typescript code snippet showing a entity class created inside the library.

the entities during serialization and deserialization, ensuring that the P21 files accurately reflect the structure and relationships of the underlying model. This approach streamlines the handling of STEP-NC data and simplifies the process for developers working with P21 files.

The library also fulfills the web-oriented requirement by leveraging the native capabilities of JavaScript and TypeScript to serialize objects and their hierarchical structures into JSON format. JSON (JavaScript Object Notation) is a widely adopted standard in modern web applications for exchanging data across APIs. This compatibility ensures that STEP-NC models can be easily served by a web server as JSON, making them accessible to web-based clients for various applications.

For example, a STEP-NC model serialized as JSON can be utilized to feed data into applications such as DTws, where real-time updates and interactions with manufacturing data are essential. This seamless integration enables the library to support web-based ecosystems, bridging the gap between STEP-NC models and modern web technologies.

```
ISO-10303-21;

HEADER;
/* Generated by the STEP-NC library from LaDPRER laboratory */

FILE_DESCRIPTION(
/* description */ ('ARM_SCHEMA: ap238_arm_schema'),
/* implementation_level */ '2;1');

FILE_NAME(
/* name */ 'test',
/* time_stamp */ '2022-10-27T15:48:58.899Z',
/* author */ ('Efrain Rodriguez'),
/* organization */ ('ladprer - unb'),
/* preprocessor_version */ 'step-nc lib v1.0',
/* originating_system */ 'various',
/* authorization */ 'all');

FILE_SCHEMA(('INTEGRATED_CNC_SCHEMA'));
ENDSEC;

DATA;
#10=PRODUCT_DEFINITION('','',#11,#12);
#11=PRODUCT_DEFINITION_FORMATION('',$,#13);
#13=MACHINING_PROJECT('','','',(#14));
#14=PRODUCT_CONTEXT('',$,'');
#12=PRODUCT_DEFINITION_CONTEXT('',$,'');
#15=MACHINING_PROJECT_WORKPIECE_RELATIONSHIP('','','',#10,#16);
#16=PRODUCT_DEFINITION('','',#17,#12);
#17=PRODUCT_DEFINITION_FORMATION('',$,#18);
#18=PRODUCT('','','',(#14));
#19=PROCESS_PRODUCT_ASSOCIATION('','',#10,#20);
#20=PRODUCT_DEFINITION_PROCESS('','',#21,'');
#21=MACHINING_WORKPLAN('test part','','','');
ENDSEC;
END-ISO-10303-21;
```

Figure 7.22: Example of P21 file generated with the STEP-NC library.

Figure 15 illustrates a STEP-NC model, previously represented in a Part 21 (P21) file, being served by a local server and displayed in JSON format within a web browser. This capability not only facilitates data exchange but also ensures compatibility with modern web-based development practices, enabling developers to create applications for digital manufacturing workflows.

The proposed STEP-NC library represents a significant step forward in addressing the limitations of existing tools for working with STEP and STEP-NC models. Its design, grounded in modern programming practices and technologies, offers a flexible, extensible, and web-oriented solution. By providing core functionality for reading and writing Part 21 files, along with the capability to serialize models into JSON for web-based applications, this library lays a robust foundation for advancing the adoption and practical application of STEP-NC in research and industry. Moreover, its open-source nature fosters collaboration and innovation, making it accessible to developers worldwide and positioning it as a tool that can grow and evolve with community contributions.

However, this is just the beginning. The library currently requires manual implementation of new entities and schemas, which can be a resource-intensive process. A significant milestone for future development is automating the generation of TypeScript classes directly from EXPRESS models, aligning with how STEP standards are formally defined. This feature would greatly enhance the library's usability, allowing it to dynamically adapt to new schemas without requiring manual intervention. Additionally, there is much room for expanding the library to support advanced features, such as richer data integration, enhanced visualization capabilities, and direct compatibility with more specialized domains of STEP and STEP-NC. Despite these current limitations, the library's modular and forward-looking architecture provides a solid framework to address these challenges in subsequent iterations, paving the way for a more comprehensive and versatile STEP-NC ecosystem.

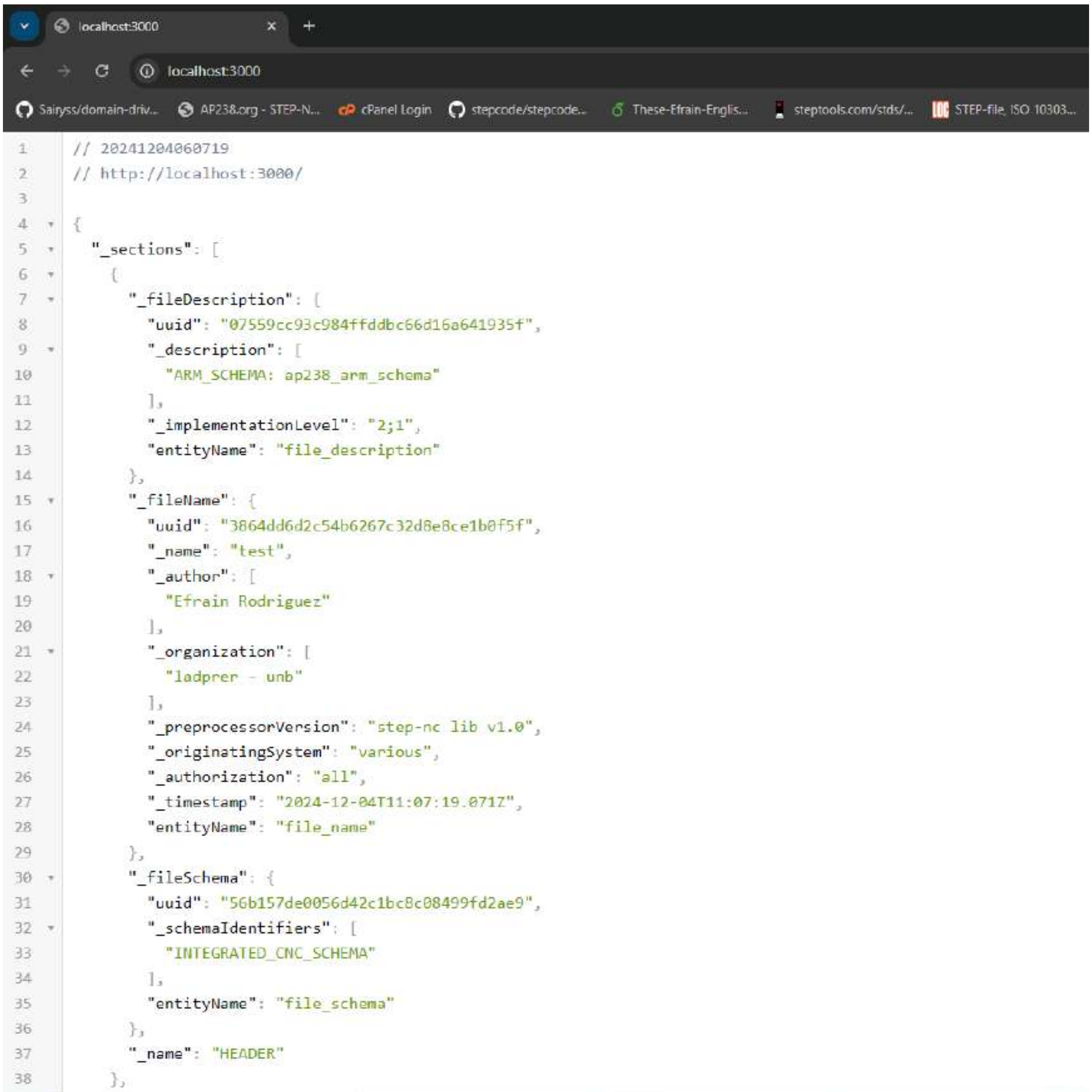


Figure 7.23: JSON response from local server using the STEP-NC library.

Chapter 8

Conclusions and Future Work

The purpose of this chapter is to present the conclusions derived from the research conducted within the scope of this thesis, highlighting the main contributions of the work as well as providing recommendations for future research.

8.1 Conclusions

This thesis proposes the development of a digital ecosystem for AM driven by standards-based DTh and DTw technologies, with STEP-NC at its core. The ecosystem proposes the integration of essential open standards such as ISO 23247, QIF, MTConnect, OPC-UA, and MQTT to enable seamless contextual data management and interoperability throughout the manufacturing lifecycle. Using STEP-NC capabilities to enrich DTh and support the development of intelligent systems such as DTws, the proposed ecosystem could facilitate improvements in information exchange, knowledge discovery, process control, and informed decision-making in AM.

In this thesis a total of 352 references were considered, comprising a diverse range of sources. The breakdown of these references is presented in Table 8.1, highlighting the emphasis on scientific articles and the inclusion of other significant sources, such as conference papers, books, and other resources. This extensive body of literature offered a comprehensive understanding of the current landscape, laying a solid foundation for identifying gaps and shaping a proposal that advances the state-of-the-art in the field.

8.1.1 Conclusion from the literature review on DTh in AM (Chapter 3)

A comprehensive review was conducted to assess the state of DTh in AM, revealing significant insights and challenges. The review identified 70 publications focusing on its integration in AM, highlighting its potential to streamline the manufacturing lifecycle through data-driven

Table 8.1: Breakdown of references reviewed in this thesis

Type of Reference	**Quantity**
Scientific Journal Articles	238
Conference Papers	22
Books	4
Other Sources	88
Total	352

approaches. Research activity has shown a clear upward trend, with notable peaks in 2018 and 2023. Significant contributions have emerged from institutions in the United States and France, together with the University of Brasília in Brazil, which produced two publications on the topic, both involving our laboratory. This underscores our active role in the advancement of the field. Furthermore, seven works listed in Table 3.1 specifically address issues related to data exchange and management in the DTh of AM processes. Most of these studies highlight STEP and STEP-NC as superior alternatives to traditional formats such as STL and G-code to support high-level DTh implementations in AM. This has led to a deeper reflection on STEP and STEP-NC as foundational standards to enable the proposed digital ecosystem.

8.1.2 Conclusion from the literature review on DTw in AM (Chapter 4)

For DTw in AM, the review revealed an exponential growth in interest, with 568 publications identified, underscoring its position as a cornerstone technology for Industry 4.0. The annual trend in research publications highlights significant momentum starting in 2016, culminating in 182 publications by 2024, a four-fold increase compared to 2020. These studies consistently emphasize the transformative potential of DTw in enabling real-time monitoring, predictive analysis, and process optimization in AM processes. Most efforts focus on specific phases of the lifecycle, as evidenced by the works listed in Table 4.3. While these studies explore DTw applications, the integrations are predominantly partial, addressing isolated aspects rather than providing a cohesive framework. Crucially, none of these works propose a standardized framework for a digital ecosystem driven by standards-based DTw and DTh.

This gap underscores the innovative contribution of this thesis, which proposes a comprehensive digital ecosystem for AM, guided by the ISO 23247 framework. ISO 23247 serves as a foundational reference for developing DTw in manufacturing, offering structured guidance for integrating DTw across lifecycle stages. Leveraging this framework, the proposed ecosystem integrates DTw and DTh technologies with standards like STEP-NC, QIF, MTConnect, OPC-UA, and MQTT, ensuring contextual data exchange and interoperability throughout the manufacturing process.

8.1.3 Conclusion from literature review on STEP-NC in AM (Chapter 5)

The literature review on STEP-NC in AM highlights the limited development of this standard within the context of AM. With only 27 publications explicitly addressing its application in AM, the research remains in its infancy, emphasizing the pressing need for extending STEP-NC models to accommodate AM-specific technological requirements. The literature review has also revealed that our laboratory is among the most active contributors to the development of this topic, with a significant portion of these contributions stemming from the work conducted in this thesis.

Although Part 17 of STEP-NC introduces entities to represent general information about AM processes, it lacks definitions tailored to specific AM technologies such as FDM and LMD. This gap presents a significant opportunity to advance the standard by proposing new STEP-NC entities designed to capture the unique characteristics of these processes. In this work, entity definitions have been proposed to represent process parameters of both FDM and LMD technologies. These contributions address critical needs in data integration and management for AM, offering a foundation for more robust and versatile STEP-NC applications. Furthermore, this work serves as a call to action for ISO TC184/SC4 to consider validating these proposed entities through practical implementations and to incorporate them into the STEP-NC standard, driving its evolution to better align with the diverse needs of modern AM technologies.

8.1.4 Conclusions from the proposed digital ecosystem (Chapter 6)

The proposed digital ecosystem for AM offers a transformative framework that seeks to integrate standards-based DTh and DTw technologies. By envisioning a cohesive and interoperable data flow across the entire manufacturing lifecycle, the ecosystem promises to enhance contextualized intelligence and enable smarter decision-making processes. Anchored in established standards such as ISO 23247, STEP, STEP-NC, QIF, MTConnect, OPC-UA, and MQTT, the ecosystem aspires to provide a unified foundation for improved data management, system interoperability, and intelligent manufacturing.

The digital ecosystem leverages the DTh as a continuous flow of data connecting all lifecycle phases, from design to inspection and maintenance. Coupled with DTw, the ecosystem could provide advanced capabilities such as real-time process monitoring, adaptive control, and predictive simulations. The incorporation of a multi-threaded architecture further amplifies these possibilities by allowing data from diverse processes and contexts to converge, enabling cross-contextual insights and lifecycle optimization. By unifying DTh and DTw technologies, the framework promises to overcome inefficiencies and enhance the traceability, adaptability, and scalability of manufacturing processes. These contributions suggest a significant step forward in bridging the gap between traditional manufacturing practices and the aspirations of Industry 4.0.

While the framework outlines a visionary path for AM, its practical realization is not without challenges. The integration of such a complex system would require significant advancements in data standardization, technological infrastructure, and workforce capabilities. Nevertheless, the proposed ecosystem offers a strategic direction for future research and development, emphasizing the importance of collaborative efforts across industry, academia, and standardization bodies. By addressing these challenges, the proposed framework holds the promise of redefining the AM landscape and advancing the broader goals of smart manufacturing.

8.1.5 Conclusions from the implementation scenarios (Chapter 7)

This thesis proposed several practical implementation scenarios, each contributing unique insights:

- **STEP-NC implementation for robotic machining**: The robotic machining scenario demonstrated the feasibility of using STEP-NC to program and simulate machining operations for an ASEA robotic arm. However, limitations such as the indirect reliance on G-code and the scarcity of open tools to fully support STEP-NC integration with robotic systems highlighted areas for future improvement. Despite these challenges, the implementation validated the adaptability of STEP-NC in robotic contexts, laying the groundwork for its broader adoption in advanced manufacturing.

- **Integration of STEP-NC and MTConnect in AM**: The implementation of STEP-NC in this scenario showcased the innovative adaptation of the existing machining-oriented data model to represent toolpaths for an FDM-based AM process. The STEP-NC program was successfully verified through simulation in the STEP-NC Machine software, which included a 3D kinematic model of the RepRap 3D printer. This integration enabled a more realistic and comprehensive simulation of the AM process. However, this approach was not without limitations. It represents an indirect implementation, as the STEP-NC program ultimately required conversion to machine-specific code for actual part fabrication. Furthermore, the adapted machining model could not fully capture all the required process information for FDM, necessitating manual modifications to include missing details, such as hotend and build plate temperatures. Despite these challenges, this novel approach contributes significantly to advancing the application of STEP-NC in AM, marking a step forward in its evolution. On the other hand, the MTConnect implementation enabled the creation of a robust real-time monitoring environment accessible via a web client, enabling the monitoring of print progress, bed and hotend temperatures, X, Y, and Z axis positions, as well as the printing speed. This system not only facilitated the visualization of key process data, such as axis positions, extrusion parameters, and build progress, but also achieved efficient data storage with high transfer rates and low delays. The implementation of both STEP-NC and MTConnect in this scenario, aligned with the proposed digital ecosystem, proved to be successful.

- **Simulation of STEP-NC programs for robotic LMD processes**: The simulation of robotic LMD toolpaths using the Kuka KR70 robot underscored the STEP-NC capability to support complex metal AM processes. The scenario highlighted the importance of integrating AM-specific kinematic models for realistic toolpath verification. However, the absence of dedicated STEP-NC entities for LMD-specific parameters, such as laser power and wire flow rate, limited its comprehensiveness. This implementation stressed the critical need for the extension of STEP-NC to include LMD-specific data and underscored the role of simulation as a bridge between digital and physical processes. Furthermore, this approach, which has not been previously documented in the literature for this type of process, represents a significant advancement in applying STEP-NC to metal AM, paving the way for future developments in this field.

- **Proposed STEP-NC models for FDM and LMD**: The development of new STEP-NC entities for FDM and LMD effectively addressed the limitations identified in earlier scenarios, offering a more comprehensive representation of these AM technologies. This work introduced EXPRESS-based models that relate data specific to FDM and LMD processes, including entities for AM operations, machine functions, and technology-specific parameters. For example, FDM-related parameters such as nozzle diameter, extrusion speed, and build plate temperature were defined, while key LMD-specific parameters like laser power, wire feed rate, and substrate thickness were also incorporated. This new data model opens significant opportunities for advancing STEP-NC implementations in FDM and LMD, offering unprecedented support for integrating these technologies into the proposed digital ecosystem. Unlike previous proposals, this STEP-NC model encompasses a wide range of parameters, addressing both the general and unique requirements of each process, and represents a significant step forward in standardizing AM technologies. However, despite the possibilities unlocked by these new models, the proposed framework requires thorough validation through real-world implementation scenarios. Such validation is essential to refine the models further and promote their eventual inclusion in official STEP-NC standards.

- **Development of a TypeScript-based STEP-NC library**: The creation of an open-source TypeScript library addressed the scarcity of modern tools for handling STEP-NC models, offering core functionalities such as serialization to Part 21 and JSON formats. These capabilities enable web-oriented applications and foster broader adoption of STEP-NC by providing developers and researchers with a versatile and accessible tool. Additionally, the library extensibility allows for the inclusion of new entities, supporting evolving STEP-NC schemas for new manufacturing requirements. However, a key limitation of the current implementation is the need for manual incorporation of new entities into the library. This manual process requires developers to analyze the EXPRESS schemas that define STEP-NC standards, translate these schemas into TypeScript classes, and integrate them into the library's structure. Each entity must adhere to the library's framework, which involves defining attributes, relationships, and serialization rules using specific decorators and inheritance patterns. While this approach ensures consistency and compatibility within the library, it is labor-intensive and prone to human error, particularly as the number of entities and the complexity of their relationships grow. To address this challenge, the library requires functionality to automate the conversion of entities defined in EXPRESS language into TypeScript classes. This automation would involve the development of a compiler-like tool capable of parsing EXPRESS schemas, extracting their definitions, and generating TypeScript code that conforms to the library architecture.

8.2 Summary of final contributions of this thesis

This thesis provides significant contributions that are summarized as follows:

- **Proposed digital ecosystem**
  - Developed a standards-based digital ecosystem integrating DTh and DTw technologies to enable more interoperable, collaborative and intelligent manufacturing systems.
  - Proposed a structured approach for integrating multiple DTh within the proposed digital ecosystem.
- **STEP-NC industrial robotic machining**
  - Demonstrated the feasibility of using STEP-NC to program and simulate robotic machining operations, highlighting the adaptability of STEP-NC in robotic contexts.
  - Developed a software adapter that converts APT machining commands into STEP-NC programs. Available in the repository in [75].
- **Integrating STEP-NC and MTConnect in AM**
  - Method to adapt the machining-oriented STEP-NC model for FDM processes.
  - Software to convert XML AM layer data to STEP-NC program. Available in the repository in [76].
  - 3D kinematic model of the RepRap Prusa 3D printer for STEP-NC Machine. Available in the repository in [77].
  - MTConnect adapter for real-time process monitoring of RepRap 3D printers.
  - Adapter code included in the Sprinter firmware. Available in the repository in [78].
- **STEP-NC simulation for LMD**

- Simulated toolpaths for robotic LMD processes, showcasing STEP-NC capability in metal AM operations.
- 3D kinematic model of the KUKA KR 70 robot for STEP-NC Machine. Available on teh repository in [79].

- **EXPRESS entities for FDM and LMD**
  - Created new EXPRESS-based STEP-NC entities tailored to FDM and LMD processes, addressing process-specific parameters such as nozzle diameter, hotend temperature, extrusion speed, laser power, and wire feed rate. This provides a call to action for ISO TC184/SC4 to consider these models for validation and inclusion in the STEP-NC standard.

- **New STEP-NC library**
  - Created an open-source, extensible TypeScript library to handle STEP-NC models, supporting serialization to Part 21 and JSON formats and enabling web-based applications.
  - Designed the library for extensibility, allowing the inclusion of new entities and schemas to adapt to evolving manufacturing requirements.
  - Addressed the lack of accessible tools for STEP-NC, making the library openly available on npm and promoting collaboration and adoption within the research and industrial communities. Available on npm in [80].
  - Pioneered novel implementations of STEP-NC for AM processes, contributing foundational knowledge and tools for its evolution in research and industry.

8.3 Future directions

Future research should prioritize the validation of the proposed STEP-NC models for FDM and LMD. Collaboration with industry stakeholders and ISO committees will be essential to ensure these models are incorporated into the official STEP-NC standard. Extending the scope of these models to include additional entities tailored to other AM processes, will further promote expansion of STEP-NC application.

The development of the STEP-NC library must also evolve to support these advancements. Currently, the manual inclusion of new entities into the library, while functional, becomes increasingly cumbersome as the complexity and size of data models grow. To address this, the library must incorporate an automated solution, such as an EXPRESS-to-TypeScript compiler, capable of generating TypeScript classes directly from EXPRESS schemas. This enhancement will require the application of compiler theory to develop a robust methodology for parsing EXPRESS schemas and translating them into TypeScript constructs. By automating this process, the library will become more scalable and adaptable, supporting the validation and adoption of new STEP-NC models with reduced development effort and increased reliability.

Leveraging artificial intelligence, particularly large language models (LLMs), offers a transformative approach to advancing the STEP-NC library. These models can efficiently analyze and interpret EXPRESS schemas directly from the standard's documentation to generate TypeScript classes for each entity definition. This automation significantly enhances efficiency, as EXPRESS schemas often encompass hundreds of interrelated entities, making manual implementation not only time-consuming but also prone to error. By ensuring that the generated classes align with the library's core structure and integration requirements, AI-driven solutions streamline the development process. Additionally, automated testing suites must complement this approach, validating the adherence of AI-generated code to the library's core structure and ensuring the reliability and functionality of the resulting models. Together, AI-based code generation and rigorous testing will enable scalable, adaptable, and robust support for evolving this library.

Additionally, the creation of web-based platforms should be pursued to provide comprehensive tools for interacting with STEP-NC data. These platforms could enable users to visualize and simulate toolpaths directly in a browser environment, including the incorporation of 3D kinematic models of manufacturing machines. Such functionality would offer an alternative to existing tools like STEP-NC Machine, providing a more accessible and modern interface. Integration with process monitoring standards, such as MTConnect, OPC UA, and MQTT, would allow these platforms to display real-time data, enabling end-to-end tracking of manufacturing processes.

Future work should focus on the validation and standardization of the proposed STEP-NC models for FDM and LMD, using the collaboration of industry and ISO committees to incorporate these advancements into the official standard. Moreover, the development of a web-based platform integrating STEP-NC with complementary standards such as QIF, MTConnect, OPC-UA, and MQTT could enhance the application of DTws in AM, enabling predictive maintenance, process optimization, and real-time monitoring. These efforts aim to bridge existing gaps, ensuring the seamless integration of standards-based DTh and DTw technologies in modern manufacturing.

The further exploration of DTw capabilities into these platforms offers another promising avenue for research and development. By combining STEP-NC data with advanced analytics powered by artificial intelligence, these DTws could provide feedback loops for predictive maintenance, process optimization, and defect detection. For example, DTws could analyze sensor data from LMD-based metal printing to predict potential defects and provide actionable recommendations to improve the process in real time. In the long term, these advancements could lead to the creation of fully interconnected ecosystems where STEP-NC serves as the backbone for contextual data management, and web platforms act as hubs for simulation, monitoring, and optimization. This vision includes the ability to simulate and validate complex manufacturing scenarios virtually before execution, leveraging AI-driven insights to make informed decisions.

By advancing these areas, the transformative potential of DTh and DTw technologies can be fully realized in AM through the proposed digital ecosystem.

References

[1] O. Kravchenko, M. Leshchenko, D. Marushchak, Y. Vdovychenko, and S. Boguslavska, "The digitalization as a global trend and growth factor of the modern economy," *SHS Web of Conferences*, vol. 65, p. 07004, may 2019. [Online]. Available: https://doi.org/10.1051/shsconf/20196507004

[2] R. Rosen, G. von Wichert, G. Lo, and K. D. Bettenhausen, "About the importance of autonomy and digital twins for the future of manufacturing," *IFAC-PapersOnLine*, vol. 48, pp. 567–572, 2015. [Online]. Available: https://doi.org/10.1016/j.ifacol.2015.06.141

[3] C. Legner, T. Eymann, T. Hess, C. Matt, T. Böhmann, P. Drews, A. Mädche, N. Urbach, and F. Ahlemann, "Digitalization: Opportunity and challenge for the business and information systems engineering community," *Business and Information Systems Engineering*, vol. 59, pp. 301–308, 8 2017. [Online]. Available: https://doi.org/10.1007/s12599-017-0484-2

[4] P. Parviainen, M. Tihinen, J. Kääriäinen, and S. Teppola, "Tackling the digitalization challenge: How to benefit from digitalization in practice," *International Journal of Information Systems and Project Management*, vol. 5, no. 1, pp. 63–77, 2017. [Online]. Available: https://doi.org/10.12821/ijispm050104

[5] A. B. Jacques; LaBerge, Laura; Mellbye, "The case for digital reinvention," *McKinsey Digital, McKinsey Company (Accessed on 8 May 2023)*, pp. 1–15, 2 2017. [Online]. Available: https://www.mckinsey.com/business-functions/mckinsey-digital/our-insights/the-case-for-digital-reinvention

[6] D. T. Ross, "Papers on automatic programming for numerically controlled machine tools," *Technical Memorandum - Servomechanisms Laboratory - Massachusetts Institute of Technology*, 1958.

[7] X. Xu, "Machine Tool 4.0 for the new era of manufacturing," *The International Journal of Advanced Manufacturing Technology*, vol. 92, no. 5-8, pp. 1893–1900, sep 2017. [Online]. Available: http://link.springer.com/10.1007/s00170-017-0300-7

[8] RS-274-D, "Standard RS-274-D: Interchangeable Variable Block Data Format for Posi-

tioning, Contouring, and Contouring/Positioning Numerically Controlled Machines," *Electronic Industries Association*, 2016.

[9] ISO 6983-1, "Numerical control of machines" Program format and definition of address words" Part1: Data format for positioning, line motion and contouring control systems," *International Standard Organization*, 2009.

[10] Q. Qi, F. Tao, T. Hu, N. Anwer, A. Liu, Y. Wei, L. Wang, and A. Nee, "Enabling technologies and tools for digital twin," *Journal of Manufacturing Systems*, oct 2019. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S027861251930086X

[11] P. Leitão, "Agent-based distributed manufacturing control: A state-of-the-art survey," *Engineering Applications of Artificial Intelligence*, vol. 22, no. 7, pp. 979–991, oct 2009. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0952197608001437

[12] J.-M. Frayret, S. D'Amours, B. Montreuil, and L. Cloutier, "A network approach to operate agile manufacturing systems," *International Journal of Production Economics*, vol. 74, no. 1-3, pp. 239–259, dec 2001. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S092552730100130X

[13] H. A. ElMaraghy, "Flexible and reconfigurable manufacturing systems paradigms," *International Journal of Flexible Manufacturing Systems*, vol. 17, no. 4, pp. 261–276, oct 2005. [Online]. Available: http://link.springer.com/10.1007/s10696-006-9028-7

[14] L. Wang, "From Intelligence Science to Intelligent Manufacturing," *Engineering*, vol. 5, no. 4, pp. 615–618, aug 2019. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2095809919301821

[15] A. J. Álvares and J. C. E. Ferreira, "WebTurning: Teleoperation of a CNC turning center through the Internet," *Journal of Materials Processing Technology*, vol. 179, no. 1-3, pp. 251–259, oct 2006. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0924013606002354

[16] R. Y. Zhong, X. Xu, E. Klotz, and S. T. Newman, "Intelligent Manufacturing in the Context of Industry 4.0: A Review," *Engineering*, vol. 3, no. 5, pp. 616–630, oct 2017. [Online]. Available: https://doi.org/10.1016/J.ENG.2017.05.015

[17] F. Tao and Q. Qi, "New it driven service-oriented smart manufacturing: Framework and characteristics," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 49, pp. 81–91, 1 2019. [Online]. Available: https://doi.org/10.1109/TSMC.2017.2723764

[18] H. Kagermann, J. Helbig, A. Hellinger, and W. Wahlster, "Securing the future of German manufacturing industry - Recommendations for implementing the strategic initiative

INDUSTRIE 4.0 - Final report of the Industrie 4.0 Working Group," *Forschungsunion-Acatech, national academy of science and engineering*, 2013.

[19] ABDI - Agência Brasileira de Desenvolvimento Industrial, "Agenda brasileira para a Indústria 4.0 O - Brasil preparado para os desafios do futuro," *Accessed on 27 May 2023*, 2018. [Online]. Available: https://www.gov.br/produtividade-e-comercio-exterior/pt-br/assuntos/noticias/mdic/mdic-e-abdi-lancam-agenda-brasileira-para-a-industria-4-0-no-forum-economico-mundial

[20] P. Zheng, H. Wang, Z. Sang, R. Y. Zhong, Y. Liu, C. Liu, K. Mubarok, S. Yu, and X. Xu, "Smart manufacturing systems for Industry 4.0: Conceptual framework, scenarios, and future perspectives," *Frontiers of Mechanical Engineering*, vol. 13, no. 2, pp. 137–150, jun 2018. [Online]. Available: http://link.springer.com/10.1007/s11465-018-0499-5

[21] X. Xu, Y. Lu, B. Vogel-Heuser, and L. Wang, "Industry 4.0 and industry 5.0—inception, conception and perception," *Journal of Manufacturing Systems*, vol. 61, pp. 530–535, 10 2021. [Online]. Available: https://doi.org/10.1016/j.jmsy.2021.10.006

[22] A. Kusiak, "Smart manufacturing," *International Journal of Production Research*, vol. 56, no. 1-2, pp. 508–517, jan 2018. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/00207543.2017.1351644

[23] NIST, "Smart manufacturing operations planning and control program," *Accessed: 27/05/2023 https://www.nist.gov/programs-projects/smart-manufacturing-operations-planning-and-control-program*, 2014.

[24] B. Wang, F. Tao, X. Fang, C. Liu, Y. Liu, and T. Freiheit, "Smart Manufacturing and Intelligent Manufacturing: A Comparative Review," *Engineering*, sep 2020. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2095809920302502

[25] B. Saenz de Ugarte, A. Artiba, and R. Pellerin, "Manufacturing execution system – a literature review," *Production Planning & Control*, vol. 20, no. 6, pp. 525–539, sep 2009. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/09537280902938613

[26] A. G. Chofreh, F. A. Goni, A. M. Shaharoun, S. Ismail, and J. J. Klemeš, "Sustainable enterprise resource planning: imperatives and research directions," *Journal of Cleaner Production*, vol. 71, pp. 139–147, may 2014. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0959652614000195

[27] J.-H. Lee and C.-O. Kim, "Multi-agent systems applications in manufacturing systems and supply chain management: a review paper," *International Journal of Production Research*, vol. 46, no. 1, pp. 233–265, jan 2008. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/00207540701441921

[28] S. Aheleroff, N. Mostashiri, X. Xu, and R. Y. Zhong, "Mass personalisation as a service in industry 4.0: A resilient response case study," *Advanced Engineering Informatics*, vol. 50, 10 2021. [Online]. Available: https://doi.org/10.1016/j.aei.2021.101438

[29] X. Xu, "From cloud computing to cloud manufacturing," *Robotics and Computer-Integrated Manufacturing*, vol. 28, no. 1, pp. 75–86, feb 2012. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0736584511000949

[30] H. Lasi, P. Fettke, H.-G. Kemper, T. Feld, and M. Hoffmann, "Industry 4.0," *Business Information Systems Engineering*, vol. 6, pp. 239–242, 8 2014. [Online]. Available: http://link.springer.com/10.1007/s12599-014-0334-4

[31] N. Mohamed, J. Al-Jaroodi, and S. Lazarova-Molnar, "Leveraging the capabilities of industry 4.0 for improving energy efficiency in smart factories," *IEEE Access*, vol. 7, pp. 18 008–18 020, 2019.

[32] D. Ivanov, A. Dolgui, J. V. Blackhurst, and T.-M. Choi, "Toward supply chain viability theory: from lessons learned through covid-19 pandemic to viable ecosystems," *International Journal of Production Research*, vol. 61, pp. 2402–2415, 4 2023. [Online]. Available: https://doi.org/10.1080/00207543.2023.2177049

[33] E. A. Lee, "Cyber physical systems: Design challenges," *2008 11th IEEE International Symposium on Object and Component-Oriented Real-Time Distributed Computing (ISORC)*, pp. 363–369, 5 2008. [Online]. Available: http://ieeexplore.ieee.org/document/4519604/

[34] L. Monostori, "Cyber-physical Production Systems: Roots, Expectations and R&D Challenges," *Procedia CIRP*, vol. 17, pp. 9–13, 2014. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2212827114003497

[35] V. Rudtsch, J. Gausemeier, J. Gesing, T. Mittag, and S. Peter, "Pattern-based business model development for cyber-physical production systems," *Procedia CIRP*, vol. 25, pp. 313–319, 2014. [Online]. Available: https://doi.org/10.1016/j.procir.2014.10.044

[36] F. Tao, Q. Qi, L. Wang, and A. Nee, "Digital Twins and Cyber–Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison," *Engineering*, vol. 5, no. 4, pp. 653–661, aug 2019. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S209580991830612X

[37] Y. Lu, C. Liu, K. I.-K. Wang, H. Huang, and X. Xu, "Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues," *Robotics and Computer-Integrated Manufacturing*, vol. 61, p. 101837, feb 2020. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0736584519302480

[38] C. Cimino, E. Negri, and L. Fumagalli, “Review of digital twin applications in manufacturing,” *Computers in Industry*, vol. 113, p. 103130, 12 2019. [Online]. Available: https://doi.org/10.1016/j.compind.2019.103130

[39] A. Mehra, “Digital twin industry worth $110.1 billion by 2028,” *MarketsandMarkets™ INC (Accessed on 23 December 2023)*, 2023. [Online]. Available: https://www.marketsandmarkets.com/PressReleases/digital-twin.asp

[40] M. Liu, S. Fang, H. Dong, and C. Xu, “Review of digital twin about concepts, technologies, and industrial applications,” *Journal of Manufacturing Systems*, vol. 58, pp. 346–361, 1 2021. [Online]. Available: https://doi.org/10.1016/j.jmsy.2020.06.017

[41] Dassault Systèmes, “3DEXPERIENCE Twin,” *(Accessed on 27 December 2023)*, 2023. [Online]. Available: https://discover.3ds.com/3d-virtual-experience-twin

[42] Siemens, “Teamcenter X,” *(Accessed on 27 December 2023)*, 2023. [Online]. Available: https://plm.sw.siemens.com/en-US/teamcenter/teamcenter-x-cloud-plm/

[43] IMB, “IBM Watson IoT Platform,” *(Accessed on 27 December 2023)*, 2023. [Online]. Available: https://internetofthings.ibmcloud.com/

[44] Microsoft, “Azure digital twins,” *(Accessed on 27 December 2023)*, 2023. [Online]. Available: https://azure.microsoft.com/en-us/products/digital-twins

[45] E. H. Glaessgen and D. S. Stargel, “The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles,” p. 1818, 2012.

[46] T. Erol, A. F. Mendi, and D. Dogan, “The digital twin revolution in healthcare,” *2020 4th International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT)*, pp. 1–7, 10 2020. [Online]. Available: https://doi.org/10.1109/ISMSIT50672.2020.9255249

[47] C. Pylianidis, S. Osinga, and I. N. Athanasiadis, “Introducing digital twins to agriculture,” *Computers and Electronics in Agriculture*, vol. 184, p. 105942, 5 2021. [Online]. Available: https://doi.org/10.1016/j.compag.2020.105942

[48] T. Deng, K. Zhang, and Z.-J. M. Shen, “A systematic review of a digital twin city: A new pattern of urban governance toward smart cities,” *Journal of Management Science and Engineering*, vol. 6, pp. 125–134, 6 2021. [Online]. Available: https://doi.org/10.1016/j.jmse.2021.03.003

[49] F. Tao and Q. Qi, “Make more digital twins,” *Nature*, vol. 573, no. 7775, pp. 490–491, sep 2019. [Online]. Available: http://www.nature.com/articles/d41586-019-02849-1

[50] H. Aydemir, U. Zengin, and U. Durak, “The digital twin paradigm for aircraft review and outlook,” *AIAA Scitech 2020 Forum*, 1 2020. [Online]. Available: https://doi.org/10.2514/6.2020-0553

[51] Boeing, “Let’s Connect: Digital Thread Advances Manufacturing,” *(Accessed on 02 January 2024)*, 2022. [Online]. Available: https://www.boeing.com/features/innovation-quarterly/2022/10/digital-thread-advances-manufacturing.page

[52] L. Martin, “Visualizing the Digital Thread and Digital Twins,” *(Accessed on 02 January 2024)*, 2021. [Online]. Available: https://www.lockheedmartin.com/en-us/news/features/2021/visualizing-the-digital-thread-and-digital-twins.html

[53] Boeing, “Digital Twin Creation,” *(Accessed on 02 January 2024)*, 2023. [Online]. Available: https://www.ge.com/research/offering/digital-twin-creation

[54] STEP Tools Inc., “Digital Thread and Digital Twin Demonstrations at Future of Flight,” *(Accessed on 02 January 2024)*, 2016. [Online]. Available: https://www.steptools.com/blog/20161005_digital_thread_demo/

[55] A. Walker, “Singapore’s digital twin – from science fiction to hi-tech reality,” *Global Infrastructure (Accessed on 02 January 2024)*, 2023. [Online]. Available: https://infra.global/singapores-digital-twin-from-science-fiction-to-hi-tech-reality/

[56] J. Warlick, R. Godziela, and D. Mitterbuchner, “Think thread first: Surf the wave of product data,” *(Accessed on 02 January 2024)*, 2023. [Online]. Available: https://www.ge.com/research/offering/digital-twin-creation

[57] C. Leiva, “Demystifying the Digital Thread and Digital Twin Concepts,” *Industry Week (Accessed on 02 January 2024)*, 2016. [Online]. Available: https://www.industryweek.com/technology-and-iiot/systems-integration/article/22007865/demystifying-the-digital-thread-and-digital-twin-concepts

[58] E. M. Kraft, “The air force digital thread/digital twin - life cycle integration and use of computational and experimental knowledge,” *54th AIAA Aerospace Sciences Meeting*, 1 2016. [Online]. Available: https://doi.org/10.2514/6.2016-0897

[59] J. V. Zweber, R. M. Kolonay, P. Kobryn, and E. J. Tuegel, “Digital thread and twin for systems engineering: Requirements to design,” *55th AIAA Aerospace Sciences Meeting*, 1 2017. [Online]. Available: https://doi.org/10.2514/6.2017-0875

[60] T. D. West and M. Blackburn, “Is digital thread/digital twin affordable? a systemic assessment of the cost of dod’s latest manhattan project,” *Procedia Computer Science*, vol. 114, pp. 47–56, 2017. [Online]. Available: https://doi.org/10.1016/j.procs.2017.09.003

[61] Q. Zhang, S. Zheng, C. Yu, Q. Wang, and Y. Ke, "Digital thread-based modeling of digital twin framework for the aircraft assembly system," *Journal of Manufacturing Systems*, vol. 65, pp. 406–420, 10 2022. [Online]. Available: https://doi.org/10.1016/j.jmsy.2022.10.004

[62] G. Bachelor, E. Brusa, D. Ferretto, and A. Mitschke, "Model-based design of complex aeronautical systems through digital twin and thread concepts," *IEEE Systems Journal*, vol. 14, pp. 1568–1579, 6 2020. [Online]. Available: https://doi.org/10.1109/JSYST.2019.2925627

[63] K. Jagusch, J. Sender, D. Jericho, and W. Flügge, "Digital thread in shipbuilding as a prerequisite for the digital twin," *Procedia CIRP*, vol. 104, pp. 318–323, 2021. [Online]. Available: https://doi.org/10.1016/j.procir.2021.11.054

[64] T. Y. Pang, J. D. P. Restrepo, C.-T. Cheng, A. Yasin, H. Lim, and M. Miletic, "Developing a digital twin and digital thread framework for an 'industry 4.0' shipyard," *Applied Sciences*, vol. 11, p. 1097, 1 2021. [Online]. Available: https://doi.org/10.3390/app11031097

[65] L. Jiang, S. Su, X. Pei, C. Chu, Y. Yuan, and K. Wang, "Product-part level digital twin modeling method for digital thread framework," *Computers Industrial Engineering*, vol. 179, p. 109168, 5 2023. [Online]. Available: https://doi.org/10.1016/j.cie.2023.109168

[66] M. Podskarbi and D. J. Knezevic, "Digital twin for operations - present applications and future digital thread," *Day 3 Wed, May 06, 2020*, 5 2020. [Online]. Available: https://doi.org/10.4043/30553-MS

[67] L. V. Monnier, G. Shao, and S. Foufou, "A methodology for digital twins of product lifecycle supported by digital thread," *Volume 2B: Advanced Manufacturing*, 10 2022. [Online]. Available: https://doi.org/10.1115/IMECE2022-95182

[68] Y. Zhang, W. Dong, J. Wang, C. Che, and L. Li, "The development of digital thread: the relations to digital twin and its industrial applications," *Digital Transformation and Society*, vol. 1, pp. 147–160, 11 2022. [Online]. Available: https://doi.org/10.1108/DTS-06-2022-0023

[69] T. Margaria and A. Schieweck, "The digital thread in industry 4.0," pp. 3–24, 2019. [Online]. Available: https://doi.org/10.1007/978-3-030-34968-4_1

[70] M. Moretti, A. Rossi, and N. Senin, "In-process monitoring of part geometry in fused filament fabrication using computer vision and digital twins," *Additive Manufacturing*, vol. 37, 1 2021. [Online]. Available: https://doi.org/10.1016/j.addma.2020.101609

[71] H. L. Wei, T. Mukherjee, W. Zhang, J. S. Zuback, G. L. Knapp, A. De, and T. DebRoy, "Mechanistic models for additive manufacturing of metallic components,"

Progress in Materials Science, vol. 116, 2 2021. [Online]. Available: https://doi.org/10.1016/j.pmatsci.2020.100703

[72] C. G. Klingaa, S. Mohanty, C. V. Funch, A. B. Hjermitslev, L. Haahr-Lillevang, and J. H. Hattel, "Towards a digital twin of laser powder bed fusion with a focus on gas flow variables," *Journal of Manufacturing Processes*, vol. 65, pp. 312–327, 5 2021. [Online]. Available: https://doi.org/10.1016/j.jmapro.2021.03.035

[73] Y. Qin, Q. Qi, P. J. Scott, and X. Jiang, "Status, comparison, and future of the representations of additive manufacturing data," *Computer-Aided Design*, vol. 111, pp. 44–64, 6 2019. [Online]. Available: https://doi.org/10.1016/j.cad.2019.02.004

[74] M. Rauch, R. Laguionie, J.-Y. Hascoet, and S.-H. Suh, "An advanced step-nc controller for intelligent machining processes," *Robotics and Computer-Integrated Manufacturing*, vol. 28, pp. 375–384, 6 2012. [Online]. Available: https://doi.org/10.1016/j.rcim.2011.11.001

[75] E. Rodriguez, "apt2stepnc - convert APT data to STEP-NC data," 2019, [Online; Accessed on March 31, 2024]. [Online]. Available: https://github.com/EfrainRodriguez/apt2stepnc

[76] ——, "STEP-NC Additive," 2019, [Online; Accessed on March 31, 2024]. [Online]. Available: https://github.com/EfrainRodriguez/additive-manufacturing-step-nc

[77] ——, "RepRap machine model Prusa Mendel for STEP-NC Machine," 2019, [Online; Accessed on March 31, 2024]. [Online]. Available: https://github.com/StepNcLadprer/RepRap-machine-model-Prusa-Mendel-for-STEP-NC-Machine

[78] ——, "Sprinter firmware with MTConnect adapter," 2019, [Online; Accessed on March 31, 2024]. [Online]. Available: https://github.com/EfrainRodriguez/Sprinter-with-MTConnect

[79] ——, "Kuka KR70 kinematic model for STEP-NC Machine," 2019, [Online; Accessed on March 31, 2024]. [Online]. Available: https://github.com/EfrainRodriguez/Kuka-robot-kr70-for-STEP-NC-Machine

[80] ——, "STEP-NC on NPM: An open-source, extensible, and runtime-friendly Javascript/Typescript library for handling STEP and STEP-NC models." 2023, [Online; Accessed on December 03, 2024]. [Online]. Available: https://www.npmjs.com/package/step-nc

[81] K. Zhou, T. Liu, and L. Zhou, "Industry 4.0: Towards future industrial opportunities and challenges," *2015 12th International Conference on Fuzzy Systems and Knowledge Discovery (FSKD)*, pp. 2147–2152, 8 2015. [Online]. Available: https://doi.org/10.1109/FSKD.2015.7382284

[82] L. D. Xu, E. L. Xu, and L. Li, "Industry 4.0: state of the art and future trends," *International Journal of Production Research*, vol. 56, pp. 2941–2962, 4 2018. [Online]. Available: https://doi.org/10.1080/00207543.2018.1444806

[83] E. Oztemel and S. Gursev, "Literature review of industry 4.0 and related technologies," *Journal of Intelligent Manufacturing*, vol. 31, pp. 127–182, 1 2020. [Online]. Available: https://doi.org/10.1007/s10845-018-1433-8

[84] A. Schumacher, S. Erol, and W. Sihn, "A maturity model for assessing industry 4.0 readiness and maturity of manufacturing enterprises," *Procedia CIRP*, vol. 52, pp. 161–166, 2016. [Online]. Available: https://doi.org/10.1016/j.procir.2016.07.040

[85] A. G. Frank, L. S. Dalenogare, and N. F. Ayala, "Industry 4.0 technologies: Implementation patterns in manufacturing companies," *International Journal of Production Economics*, vol. 210, pp. 15–26, 4 2019. [Online]. Available: https://doi.org/10.1016/j.ijpe.2019.01.004

[86] M. Hermann, T. Pentek, and B. Otto, "Design principles for industrie 4.0 scenarios: A literature review," *Working paper - Technische Universität Dortmund*, 2015.

[87] VDI/VDE, "Reference architecture model industrie 4.0 (rami4.0)," *GMA - Status Report*, 07 2015.

[88] P. Monteiro, M. Carvalho, F. Morais, M. Melo, R. J. Machado, and F. Pereira, "Adoption of architecture reference models for industrial information management systems," *2018 International Conference on Intelligent Systems (IS)*, pp. 763–770, 9 2018. [Online]. Available: https://doi.org/10.1109/IS.2018.8710550

[89] G. Steindl, M. Stagl, L. Kasper, W. Kastner, and R. Hofmann, "Generic digital twin architecture for industrial energy systems," *Applied Sciences*, vol. 10, p. 8903, 12 2020. [Online]. Available: https://doi.org/10.3390/app10248903

[90] M. A. Pisching, M. A. Pessoa, F. Junqueira, D. J. dos Santos Filho, and P. E. Miyagi, "An architecture based on rami 4.0 to discover equipment to process operations required by products," *Computers Industrial Engineering*, vol. 125, pp. 574–591, 11 2018. [Online]. Available: https://doi.org/10.1016/j.cie.2017.12.029

[91] P. F. S. de Melo and E. P. Godoy, "Controller interface for industry 4.0 based on rami 4.0 and opc ua," *2019 II Workshop on Metrology for Industry 4.0 and IoT (MetroInd4.0IoT)*, pp. 229–234, 6 2019. [Online]. Available: https://doi.org/10.1109/METROI4.2019.8792837

[92] G. H. Schaffer, "Artificial intelligence: a tool for smart manufacturing," *American Machinist and Automated Manufacturing*, vol. 130, p. 83, 1986.

[93] J. Krakauer, "Smart manufacturing with artificial," *Computer and Automated Systems Association of the Society of Manufacturing Engineers*, 1987.

[94] J. Davis, T. Edgar, J. Porter, J. Bernaden, and M. Sarli, "Smart manufacturing, manufacturing intelligence and demand-dynamic performance," *Computers Chemical Engineering*, vol. 47, pp. 145–156, 12 2012. [Online]. Available: https://doi.org/10.1016/j.compchemeng.2012.06.037

[95] F. Tao, Q. Qi, A. Liu, and A. Kusiak, "Data-driven smart manufacturing," *Journal of Manufacturing Systems*, vol. 48, pp. 157–169, jul 2018. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0278612518300062

[96] Y. Lu, K. C. Morris, and S. Frechette, "Standards landscape and directions for smart manufacturing systems." IEEE, 8 2015, pp. 998–1005. [Online]. Available: https://doi.org/10.1109/CoASE.2015.7294229

[97] Y. Lu, K. Morris, and S. Frechette, "Current standards landscape for smart manufacturing systems," *(Accessed January 18, 2024)*, no. 8107, 2 2016. [Online]. Available: https://www.nist.gov/publications/current-standards-landscape-smart-manufacturing-systems

[98] W. Z. Bernstein, T. D. Hedberg, M. Helu, and A. B. Feeney, "Contextualising manufacturing data for lifecycle decision-making," *International Journal of Product Lifecycle Management*, vol. 10, p. 326, 2017. [Online]. Available: https://doi.org/10.1504/IJPLM.2017.090328

[99] A. B. Feeney, M. Sharp, and S. Krima, "Digital thread for smart manufacturing," 2018. [Online]. Available: https://www.nist.gov/programs-projects/digital-thread-smart-manufacturing

[100] R. R. Lipman, A. B. Feeney, and S. Krima, "Product definitions for smart manufacturing," 2022. [Online]. Available: https://www.nist.gov/programs-projects/product-definitions-smart-manufacturing

[101] P. O'Donovan, K. Leahy, K. Bruton, and D. T. J. O'Sullivan, "An industrial big data pipeline for data-driven analytics maintenance applications in large-scale smart manufacturing facilities," *Journal of Big Data*, vol. 2, p. 25, 12 2015. [Online]. Available: https://doi.org/10.1186/s40537-015-0034-z

[102] T. Margaria, D. Pesch, and A. McGibney, "Digital thread in smart manufacturing," pp. 179–183, 2022. [Online]. Available: https://doi.org/10.1007/978-3-031-19762-8_12

[103] D. Broman, E. A. Lee, S. Tripakis, and M. Törngren, "Viewpoints, formalisms, languages, and tools for cyber-physical systems," *Proceedings of the 6th International*

Workshop on Multi-Paradigm Modeling, pp. 49–54, 10 2012. [Online]. Available: https://doi.org/10.1145/2508443.2508452

[104] L. Hu, N. Xie, Z. Kuang, and K. Zhao, "Review of cyber-physical system architecture," *2012 IEEE 15th International Symposium on Object/Component/Service-Oriented Real-Time Distributed Computing Workshops*, pp. 25–30, 4 2012. [Online]. Available: https://doi.org/10.1109/ISORCW.2012.15

[105] Y. Liu, Y. Peng, B. Wang, S. Yao, and Z. Liu, "Review on cyber-physical systems," *IEEE/CAA Journal of Automatica Sinica*, vol. 4, pp. 27–40, 1 2017. [Online]. Available: http://ieeexplore.ieee.org/document/7815549/

[106] H. J. La and S. D. Kim, "A service-based approach to designing cyber physical systems," *2010 IEEE/ACIS 9th International Conference on Computer and Information Science*, pp. 895–900, 8 2010. [Online]. Available: https://doi.org/10.1109/ICIS.2010.73

[107] J. Lee, B. Bagheri, and H.-A. Kao, "A cyber-physical systems architecture for industry 4.0-based manufacturing systems," *Manufacturing Letters*, vol. 3, pp. 18–23, 1 2015. [Online]. Available: https://doi.org/10.1016/j.mfglet.2014.12.001

[108] J.-R. Jiang, "An improved cyber-physical systems architecture for industry 4.0 smart factories," *2017 International Conference on Applied System Innovation (ICASI)*, pp. 918–920, 5 2017. [Online]. Available: https://doi.org/10.1109/ICASI.2017.7988589

[109] L. Monostori, B. Kádár, T. Bauernhansl, S. Kondoh, S. Kumara, G. Reinhart, O. Sauer, G. Schuh, W. Sihn, and K. Ueda, "Cyber-physical systems in manufacturing," *CIRP Annals*, vol. 65, no. 2, pp. 621–641, 2016. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0007850616301974

[110] V. Gunes, S. Peter, T. Givargis, and F. Vahih, "A survey on concepts, applications, and challenges in cyber-physical systems," *KSII Transactions on Internet and Information Systems*, vol. 8, 12 2014. [Online]. Available: https://doi.org/10.3837/tiis.2014.12.001

[111] T. H.-J. Uhlemann, C. Lehmann, and R. Steinhilper, "The digital twin: Realizing the cyber-physical production system for industry 4.0," *Procedia CIRP*, vol. 61, pp. 335–340, 2017. [Online]. Available: https://doi.org/10.1016/j.procir.2016.11.152

[112] Y. Lu and F. Ju, "Smart manufacturing systems based on cyber-physical manufacturing services (cpms)," *IFAC-PapersOnLine*, vol. 50, pp. 15 883–15 889, 7 2017. [Online]. Available: https://doi.org/10.1016/j.ifacol.2017.08.2349

[113] D. A. Rossit, F. Tohmé, and M. Frutos, "Production planning and scheduling in cyber-physical production systems: a review," *International Journal of Computer*

Integrated Manufacturing, vol. 32, pp. 385–395, 5 2019. [Online]. Available: https://doi.org/10.1080/0951192X.2019.1605199

[114] K. Ding, F. T. Chan, X. Zhang, G. Zhou, and F. Zhang, "Defining a Digital Twin-based Cyber-Physical Production System for autonomous manufacturing in smart shop floors," *International Journal of Production Research*, vol. 57, no. 20, pp. 6315–6334, oct 2019. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/00207543.2019.1566661

[115] E. Francalanza, J. Borg, and C. Constantinescu, "A knowledge-based tool for designing cyber physical production systems," *Computers in Industry*, vol. 84, pp. 39–58, 1 2017. [Online]. Available: https://doi.org/10.1016/j.compind.2016.08.001

[116] K. Ashton, "That 'internet of things' thing - in the real world, things matter more than ideas." *(Accessed on January 21, 2024)*, 6 2009. [Online]. Available: https://www.rfidjournal.com/that-internet-of-things-thing

[117] L. Atzori, A. Iera, and G. Morabito, "The internet of things: A survey," *Computer Networks*, vol. 54, pp. 2787–2805, 10 2010. [Online]. Available: https://doi.org/10.1016/j.comnet.2010.05.010

[118] H. A. Zainab, A. A. Hesham, and M. B. Mahmoud, "Internet of things (iot): Definitions, challenges and recent research directions," *International Journal of Computer Applications*, vol. 128, pp. 37–47, 10 2015. [Online]. Available: https://doi.org/10.5120/ijca2015906430

[119] S. Chen, H. Xu, D. Liu, B. Hu, and H. Wang, "A vision of iot: Applications, challenges, and opportunities with china perspective," *IEEE Internet of Things Journal*, vol. 1, pp. 349–359, 8 2014. [Online]. Available: https://doi.org/10.1109/JIOT.2014.2337336

[120] G. Lampropoulos, K. Siakas, and T. Anastasiadis, "Internet of things in the context of industry 4.0: An overview," *International Journal of Entrepreneurial Knowledge*, vol. 7, pp. 4–19, 6 2019. [Online]. Available: https://doi.org/10.2478/ijek-2019-0001

[121] H. Yang, S. Kumara, S. T. Bukkapatnam, and F. Tsung, "The internet of things for smart manufacturing: A review," *IISE Transactions*, vol. 51, pp. 1190–1216, 11 2019. [Online]. Available: https://doi.org/10.1080/24725854.2018.1555383

[122] P. Sethi and S. R. Sarangi, "Internet of things: Architectures, protocols, and applications," *Journal of Electrical and Computer Engineering*, vol. 2017, pp. 1–25, 2017. [Online]. Available: https://doi.org/10.1155/2017/9324035

[123] P. Ray, "A survey on internet of things architectures," *Journal of King Saud University - Computer and Information Sciences*, vol. 30, pp. 291–319, 7 2018. [Online]. Available: https://doi.org/10.1016/j.jksuci.2016.10.003

[124] H. Boyes, B. Hallaq, J. Cunningham, and T. Watson, “The industrial internet of things (iiot): An analysis framework,” *Computers in Industry*, vol. 101, pp. 1–12, 10 2018. [Online]. Available: https://doi.org/10.1016/j.compind.2018.04.015

[125] I. I. C. (IIC), “The industrial internet of things volume g1: Reference architecture,” 06 2019. [Online]. Available: https://www.iiconsortium.org/pdf/IIRA-v1.9.pdf

[126] J. Li, J.-J. Qiu, Y. Zhou, S. Wen, K.-Q. Dou, and Q. Li, “Study on the reference architecture and assessment framework of industrial internet platform,” *IEEE Access*, vol. 8, pp. 164 950–164 971, 2020. [Online]. Available: https://doi.org/10.1109/ACCESS.2020.3021719

[127] Y. Lu, X. Xu, and L. Wang, “Smart manufacturing process and system automation – A critical review of the standards and envisioned scenarios,” *Journal of Manufacturing Systems*, vol. 56, pp. 312–325, jul 2020. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S027861252030100X

[128] I. 10303-203, “Industrial automation systems and integration - Product data representation and exchange - Part 203: Application protocol: Configuration controlled 3D design of mechanical parts and assemblies,” *International Standard Organization*, 2011.

[129] I. 10303-214, “Industrial automation systems and integration - Product data representation and exchange - Part 214: Application protocol: Core data for automotive mechanical design processes,” *International Standard Organization*, 2010.

[130] I. 10303-242, “Industrial automation systems and integration - Product data representation and exchange - Part 242: Application protocol: Managed model-based 3D engineering,” *International Standard Organization*, 2022.

[131] I. 23952, “Automation systems and integration - Quality information framework (QIF) - An integrated model for manufacturing quality information,” *International Standard Organization*, 2020.

[132] I. 14649-1, “Industrial automation systems and integration - Physical device control - Data model for computerized numerical controllers,” *International Standard Organization*, 2003.

[133] I. 10303-238, “Industrial automation systems and integration - Product data representation and exchange - Part 238: Application protocol: Model based integrated manufacturing,” *International Standard Organization*, 2022.

[134] I. 22093, “Industrial automation systems and integration - Physical device control - Dimensional Measuring Interface Standard (DMIS),” *International Standard Organization*, 2011.

[135] ANSI/MTC1.4, "MTConnect Standard," *AMT-The Association For Manufacturing Technology*, 2018.

[136] OPC-UA, "OPC Unified Architecture (UA)," *OPC Foundation - The Industrial Interoperability Standard*, 2008.

[137] I. 23247-1, "Automation systems and integration — Digital Twin framework for manufacturing — Part 1: Overview and general principles," *International Standard Organization*, 2021.

[138] I. 23704-1, "General requirements for cyber-physically controlled smart machine tool systems (CPSMT) - Part 1: Overview and fundamental principles," *International Standard Organization*, 2022.

[139] I. 23704-2, "General requirements for cyber-physically controlled smart machine tool systems (CPSMT) - Part 2: Reference architecture of CPSMT for subtractive manufacturing," *International Standard Organization*, 2022.

[140] I. 23704-3, "General requirements for cyber-physically controlled smart machine tool systems (CPSMT) - Part 3: Reference architecture of CPSMT for additive manufacturing," *International Standard Organization*, 2023.

[141] W. Luo, T. Hu, C. Zhang, and Y. Wei, "Digital twin for CNC machine tool: modeling and using strategy," *Journal of Ambient Intelligence and Humanized Computing*, vol. 10, no. 3, pp. 1129–1140, mar 2019. [Online]. Available: http://link.springer.com/10.1007/s12652-018-0946-5

[142] C. Liu and X. Xu, "Cyber-physical machine tool – the era of machine tool 4.0," *Procedia CIRP*, vol. 63, pp. 70–75, 2017. [Online]. Available: https://doi.org/10.1016/j.procir.2017.03.078

[143] C. Liu, P. Zheng, and X. Xu, "Digitalisation and servitisation of machine tools in the era of industry 4.0: a review," *International Journal of Production Research*, vol. 61, pp. 4069–4101, 6 2023. [Online]. Available: https://doi.org/10.1080/00207543.2021.1969462

[144] C. Liu, H. Vengayil, Y. Lu, and X. Xu, "A cyber-physical machine tools platform using opc ua and mtconnect," *Journal of Manufacturing Systems*, vol. 51, pp. 61–74, 4 2019. [Online]. Available: https://doi.org/10.1016/j.jmsy.2019.04.006

[145] A. J. Álvares, L. E. S. de Oliveira, and J. C. E. Ferreira, "Development of a cyber-physical framework for monitoring and teleoperation of a cnc lathe based on mtconnect and opc protocols," *International Journal of Computer Integrated Manufacturing*, vol. 31, pp. 1049–1066, 11 2018. [Online]. Available: https://doi.org/10.1080/0951192X.2018.1493232

[146] E. Rodriguez, J. P. Rodriguez, A. J. Alvares, C. Riaño, and L. E. de Oliveira, "Developing a MTConnect Framework for RepRap Additive Manufacturing Machines," *IFAC-PapersOnLine*, vol. 52, no. 13, pp. 2507–2512, 2019. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2405896319315708

[147] IEC TR 62541-1, "OPC Unified Architecture - Part 1: Overview and concepts," *International Electrotechnical Commission*, 2020.

[148] HiveMQ, "MQTT Tutorial: An Easy Guide to Getting Started with MQTT," *(Accessed on February 8, 2024)*, 2024. [Online]. Available: https://www.hivemq.com/article/how-to-get-started-with-mqtt/

[149] I. 20922, "Information technology — Message Queuing Telemetry Transport (MQTT) v3.1.1," *International Standard Organization*, 2016.

[150] O. Abdulhameed, A. Al-Ahmari, W. Ameen, and S. H. Mian, "Additive manufacturing: Challenges, trends, and applications," *Advances in Mechanical Engineering*, vol. 11, p. 168781401882288, 2 2019. [Online]. Available: https://doi.org/10.1177/1687814018822880

[151] ISO/ASTM 52900, "Additive manufacturing — General principles — Fundamentals and vocabulary," *International Standard Organization*, 2021.

[152] P. Reeves, C. Tuck, and R. Hague, "Additive Manufacturing for Mass Customization," 2011, pp. 275–289. [Online]. Available: http://link.springer.com/10.1007/978-1-84996-489-0{_}13

[153] R. M. Mahamood and E. T. Akinlabi, "Achieving Mass Customization Through Additive Manufacturing," 2016, pp. 385–390. [Online]. Available: http://link.springer.com/10.1007/978-3-319-41697-7{_}34

[154] Y. Zhang, A. Bernard, R. Harik, and G. Fadel, "A new method for single-layer-part nesting in additive manufacturing," *Rapid Prototyping Journal*, vol. 24, no. 5, pp. 840–854, jul 2018. [Online]. Available: https://doi.org/10.1108/RPJ-01-2017-0008

[155] R. Liu, Z. Wang, T. Sparks, F. Liou, and J. Newkirk, "Aerospace applications of laser additive manufacturing," in *Laser Additive Manufacturing*. Elsevier, 2017, pp. 351–371. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/B9780081004333000130

[156] E. Uhlmann, R. Kersting, T. B. Klein, M. F. Cruz, and A. V. Borille, "Additive Manufacturing of Titanium Alloy for Aircraft Components," *Procedia CIRP*, vol. 35, pp. 55–60, 2015. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2212827115009154

[157] R. Leal, F. M. Barreiros, L. Alves, F. Romeiro, J. C. Vasco, M. Santos, and C. Marto, "Additive manufacturing tooling for the automotive industry," *The International Journal of Advanced Manufacturing Technology*, vol. 92, no. 5-8, pp. 1671–1676, sep 2017. [Online]. Available: http://link.springer.com/10.1007/s00170-017-0239-8

[158] P. Szymczyk-Ziółkowska, M. B. Łabowska, J. Detyna, I. Michalak, and P. Gruber, "A review of fabrication polymer scaffolds for biomedical applications using additive manufacturing techniques," *Biocybernetics and Biomedical Engineering*, vol. 40, no. 2, pp. 624–638, apr 2020. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0208521620300206

[159] D. Delgado Camacho, P. Clayton, W. J. O'Brien, C. Seepersad, M. Juenger, R. Ferron, and S. Salamone, "Applications of additive manufacturing in the construction industry – A forward-looking review," *Automation in Construction*, vol. 89, pp. 110–119, may 2018. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0926580517307847

[160] J. Bromberger and R. Kelly, "Additive Manufacturing: A Long-Term Game Changer for Manufactures," *McKinsey & Company Operations*, pp. Accessed December 2, 2019. https://www.mckinsey.com/business–functions/operations/our–insights/additive–manufacturing–a–long–term–game–changer–for–manufacturers, 2017.

[161] E. Rodriguez, A. J. Alvares, and C. I. Jaimes, "Conceptual design and dimensional optimization of the linear delta robot with single legs for additive manufacturing," *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, vol. 233, no. 7, pp. 855–869, aug 2019. [Online]. Available: http://journals.sagepub.com/doi/10.1177/0959651819836915

[162] U. Bruder, "Rapid Prototyping and Additive Manufacturing," in *User's Guide to Plastic*. München: Carl Hanser Verlag GmbH & Co. KG, jul 2019, pp. 154–167. [Online]. Available: https://www.hanser-elibrary.com/doi/10.3139/9781569907351.018

[163] Siemens, "Additive Manufacturing for the Energy Industry," *Accessed April 17, 2020: https://new.siemens.com/global/en/products/energy/topics/additive-manufacturing.html*, 2020.

[164] V. T. Le, H. Paris, and G. Mandil, "Process planning for combined additive and subtractive manufacturing technologies in a remanufacturing context," *Journal of Manufacturing Systems*, vol. 44, pp. 243–254, jul 2017. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0278612517301024

[165] M. Leino, J. Pekkarinen, and R. Soukka, "The Role of Laser Additive Manufacturing Methods of Metals in Repair, Refurbishment and Remanufacturing – Enabling Circular

Economy," *Physics Procedia*, vol. 83, pp. 752–760, 2016. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1875389216301845

[166] S. H. Khajavi, J. Partanen, and J. Holmström, "Additive manufacturing in the spare parts supply chain," *Computers in Industry*, vol. 65, no. 1, pp. 50–63, jan 2014. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0166361513001565

[167] P. Liu, S. H. Huang, A. Mokasdar, H. Zhou, and L. Hou, "The impact of additive manufacturing in the aircraft spare parts supply chain: supply chain operation reference (scor) model based analysis," *Production Planning & Control*, vol. 25, no. 13-14, pp. 1169–1181, oct 2014. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/09537287.2013.808835

[168] D.-G. Ahn, "Directed Energy Deposition (DED) Process: State of the Art," *International Journal of Precision Engineering and Manufacturing-Green Technology*, vol. 8, pp. 703–742, 3 2021. [Online]. Available: https://doi.org/10.1007/s40684-020-00302-7

[169] M.-A. de Pastre, Y. Quinsat, and C. Lartigue, "Effects of additive manufacturing processes on part defects and properties: a classification review," *International Journal on Interactive Design and Manufacturing (IJIDeM)*, vol. 16, pp. 1471–1496, 12 2022. [Online]. Available: https://doi.org/10.1007/s12008-022-00839-8

[170] A. Gasser, G. Backes, I. Kelbassa, A. Weisheit, and K. Wissenbach, "Laser additive manufacturing," *Laser Technik Journal*, vol. 7, pp. 58–63, 2 2010. [Online]. Available: https://doi.org/10.1002/latj.201090029

[171] Meltio, "Meltio M450," *(Accessed on January 27, 2024)*, 2024. [Online]. Available: https://meltio3d.com/metal-3d-printers/meltio-m450/

[172] D. J. Braconnier, R. E. Jensen, and A. M. Peterson, "Processing parameter correlations in material extrusion additive manufacturing," *Additive Manufacturing*, vol. 31, p. 100924, 1 2020. [Online]. Available: https://doi.org/10.1016/j.addma.2019.100924

[173] V. Dhinakaran, K. M. Kumar, P. B. Ram, M. Ravichandran, and M. Vinayagamoorthy, "A review on recent advancements in fused deposition modeling," *Materials Today: Proceedings*, vol. 27, pp. 752–756, 2020. [Online]. Available: https://doi.org/10.1016/j.matpr.2019.12.036

[174] A. Corallo, M. E. Latino, M. Lazoi, S. Lettera, M. Marra, and S. Verardi, "Defining product lifecycle management: A journey across features, definitions, and concepts," *ISRN Industrial Engineering*, vol. 2013, pp. 1–10, 8 2013. [Online]. Available: https://doi.org/10.1155/2013/170812

[175] S. Terzi, A. Bouras, D. Dutta, M. Garetti, and D. Kiritsis, “Product lifecycle management amp;ndash; from its history to its new role,” *International Journal of Product Lifecycle Management*, vol. 4, p. 360, 2010. [Online]. Available: https://doi.org/10.1504/IJPLM.2010.036489

[176] S. Lee, Y.-S. Ma, G. Thimm, and J. Verstraeten, “Product lifecycle management in aviation maintenance, repair and overhaul,” *Computers in Industry*, vol. 59, pp. 296–303, 3 2008. [Online]. Available: https://doi.org/10.1016/j.compind.2007.06.022

[177] T.-A. Chiang and A. J. Trappey, “Development of value chain collaborative model for product lifecycle management and its lcd industry adoption,” *International Journal of Production Economics*, vol. 109, pp. 90–104, 9 2007. [Online]. Available: https://doi.org/10.1016/j.ijpe.2006.11.005

[178] T. D. West and A. Pyster, “Untangling the digital thread: The challenge and promise of model-based engineering in defense acquisition,” *INSIGHT*, vol. 18, pp. 45–55, 8 2015. [Online]. Available: https://doi.org/10.1002/inst.12022

[179] E. Kraft, “Expanding the digital thread to impact total ownership cost,” *NIST MBE Summit*, 12 2013.

[180] T. Hedberg, J. Lubell, L. Fischer, L. Maggiano, and A. B. Feeney, “Testing the digital thread in support of model-based manufacturing and inspection,” *Journal of Computing and Information Science in Engineering*, vol. 16, 6 2016. [Online]. Available: https://doi.org/10.1115/1.4032697

[181] T. Hedberg, A. B. Feeney, M. Helu, and J. A. Camelio, “Toward a lifecycle information framework and technology in manufacturing,” *Journal of Computing and Information Science in Engineering*, vol. 17, 6 2017. [Online]. Available: https://doi.org/10.1115/1.4034132

[182] E. Kraft, “Hpcmp createamp;trade;-av and the air force digital thread,” *53rd AIAA Aerospace Sciences Meeting*, 1 2015. [Online]. Available: https://doi.org/10.2514/6.2015-0042

[183] D. B. Kim, P. Witherell, R. Lipman, and S. C. Feng, “Streamlining the additive manufacturing digital spectrum: A systems approach,” *Additive Manufacturing*, vol. 5, pp. 20–30, 1 2015. [Online]. Available: https://doi.org/10.1016/j.addma.2014.10.004

[184] D. Mies, W. Marsden, and S. Warde, “Overview of additive manufacturing informatics: “a digital thread”,” *Integrating Materials and Manufacturing Innovation*, vol. 5, pp. 114–142, 12 2016. [Online]. Available: https://doi.org/10.1186/s40192-016-0050-7

[185] D. B. Kim, "An approach for composing predictive models from disparate knowledge sources in smart manufacturing environments," *Journal of Intelligent Manufacturing*, vol. 30, pp. 1999–2012, 4 2019. [Online]. Available: https://doi.org/10.1007/s10845-017-1366-7

[186] R. Bonnard, J.-Y. Hascoët, and P. Mognol, "Data model for additive manufacturing digital thread: state of the art and perspectives," *International Journal of Computer Integrated Manufacturing*, vol. 32, pp. 1170–1191, 12 2019. [Online]. Available: https://doi.org/10.1080/0951192X.2019.1690681

[187] M. Helu and T. Hedberg, "Enabling smart manufacturing research and development using a product lifecycle test bed," *Procedia Manufacturing*, vol. 1, pp. 86–97, 2015. [Online]. Available: https://doi.org/10.1016/j.promfg.2015.09.066

[188] T. D. Hedberg, M. Bajaj, and J. A. Camelio, "Using graphs to link data across the product lifecycle for enabling smart manufacturing digital threads," *Journal of Computing and Information Science in Engineering*, vol. 20, 2 2020. [Online]. Available: https://doi.org/10.1115/1.4044921

[189] S. Kwon, L. V. Monnier, R. Barbau, and W. Z. Bernstein, "Enriching standards-based digital thread by fusing as-designed and as-inspected data using knowledge graphs," *Advanced Engineering Informatics*, vol. 46, p. 101102, 10 2020. [Online]. Available: https://doi.org/10.1016/j.aei.2020.101102

[190] M. Helu, T. Hedberg, and A. B. Feeney, "Reference architecture to integrate heterogeneous manufacturing systems for the digital thread," *CIRP Journal of Manufacturing Science and Technology*, vol. 19, pp. 191–195, 11 2017. [Online]. Available: https://doi.org/10.1016/j.cirpj.2017.04.002

[191] M. Helu, A. Joseph, and T. Hedberg, "A standards-based approach for linking as-planned to as-fabricated product data," *CIRP Annals*, vol. 67, pp. 487–490, 2018. [Online]. Available: https://doi.org/10.1016/j.cirp.2018.04.039

[192] V. Singh and K. E. Willcox, "Engineering design with digital thread," *2018 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, 1 2018. [Online]. Available: https://doi.org/10.2514/6.2018-0569

[193] ——, "Decision-making under uncertainty for a digital thread-enabled design process," *Journal of Mechanical Design*, vol. 143, 9 2021. [Online]. Available: https://doi.org/10.1115/1.4050108

[194] A. Gharbi, D. Sarojini, E. Kallou, D. J. Harper, V. Petitgenet, D. Rancourt, S. I. Briceno, and D. N. Mavris, "A single digital thread approach to aircraft

detailed design," *55th AIAA Aerospace Sciences Meeting*, 1 2017. [Online]. Available: https://doi.org/10.2514/6.2017-0693

[195] D. J. L. Siedlak, O. J. Pinon, P. R. Schlais, T. M. Schmidt, and D. N. Mavris, "A digital thread approach to support manufacturing-influenced conceptual aircraft design," *Research in Engineering Design*, vol. 29, pp. 285–308, 4 2018. [Online]. Available: https://doi.org/10.1007/s00163-017-0269-0

[196] N. Eskue, "Digital thread roadmap for manufacturing and health monitoring the life cycle of composite aerospace components," *Aerospace*, vol. 10, p. 146, 2 2023. [Online]. Available: https://doi.org/10.3390/aerospace10020146

[197] A. R. Nassar and W. Reutzel, "A proposed digital thread for additive manufacturing," *Applied Research Laboratory, The Pennsylvania State University*, 2013.

[198] B. Vogel-Heuser and D. Hess, "Guest editorial industry 4.0–prerequisites and visions," *IEEE Transactions on Automation Science and Engineering*, vol. 13, pp. 411–413, 4 2016. [Online]. Available: https://doi.org/10.1109/TASE.2016.2523639

[199] D. B. Kim, P. Witherell, Y. Lu, and S. Feng, "Toward a digital thread and data package for metals-additive manufacturing," *Smart and Sustainable Manufacturing Systems*, vol. 1, p. 20160003, 2 2017. [Online]. Available: https://doi.org/10.1520/SSMS20160003

[200] R. R. Lipman and J. S. McFarlane, "Exploring model-based engineering concepts for additive manufacturing," *Proceedings of the 26th Solid Freeform Fabrication Symposium*, 8 2015.

[201] R. Bonnard, J.-Y. Hascoët, P. Mognol, E. Zancul, and A. J. Alvares, "Hierarchical object-oriented model (hoom) for additive manufacturing digital thread," *Journal of Manufacturing Systems*, vol. 50, pp. 36–52, 1 2019. [Online]. Available: https://doi.org/10.1016/j.jmsy.2018.11.003

[202] A. Kumar, P. Kumar, R. K. Mittal, and H. Singh, *Printing file formats for additive manufacturing technologies*. Elsevier, 2023, pp. 87–102. [Online]. Available: https://doi.org/10.1016/B978-0-323-91834-3.00006-5

[203] 3D Systems, "Stereolithography interface specification," 1989.

[204] M. Szilvśi-Nagy and G. Mátyási, "Analysis of stl files," *Mathematical and Computer Modelling*, vol. 38, pp. 945–960, 10 2003. [Online]. Available: https://doi.org/10.1016/S0895-7177(03)90079-3

[205] I. Stroud and P. Xirouchakis, "Stl and extensions," *Advances in Engineering Software*, vol. 31, pp. 83–95, 2 2000. [Online]. Available: https://doi.org/10.1016/S0965-9978(99)00046-0

[206] T. Wu and E. H. M. Cheung, "Enhanced stl," *The International Journal of Advanced Manufacturing Technology*, vol. 29, pp. 1143–1150, 8 2006. [Online]. Available: https://doi.org/10.1007/s00170-005-0001-5

[207] ISO/ASTM-52915, "Specification for additive manufacturing file format (AMF) Version 1.2," *International Standard Organization*, 2020.

[208] J. D. Hiller and H. Lipson, "Stl 2.0: A proposal for a universal multi-material additive manufacturing file format," *International Solid Freeform Fabrication Symposium*, 2009.

[209] R. Paul and S. Anand, "A new steiner patch based file format for additive manufacturing processes," *Computer-Aided Design*, vol. 63, pp. 86–100, 6 2015. [Online]. Available: https://doi.org/10.1016/j.cad.2015.01.002

[210] K.-M. Yu, Y. Wang, and C. C. Wang, "Smooth geometry generation in additive manufacturing file format: problem study and new formulation," *Rapid Prototyping Journal*, vol. 23, pp. 34–43, 1 2017. [Online]. Available: https://doi.org/10.1108/RPJ-06-2015-0067

[211] 3MF Consortium, "3d manufacturing format (3mf) - the file format for 3d printing," *(Accessed on January 30, 2024)*, 2014.

[212] Wavefront Technologies, "Wavefront advanced visualiser manual— appendix b1. object files (.obj)," 1995.

[213] D. Ramey, L. Rose, and L. Tyermann, "Mtl material format (lightwave, obj)," *Wavefront Technologies*, 1995.

[214] E. Rodriguez, R. Bonnard, and A. Alvares, "Proposal of an advanced data model for step-nc compliant additive manufacturing," *Procceedings of the 24th ABCM International Congress of Mechanical Engineering*, 2017. [Online]. Available: https://doi.org/10.26678/ABCM.COBEM2017.COB17-2435

[215] J. Xiao, N. Anwer, A. Durupt, J. L. Duigou, and B. Eynard, "Information exchange standards for design, tolerancing and additive manufacturing: a research review," *International Journal on Interactive Design and Manufacturing (IJIDeM)*, vol. 12, pp. 495–504, 5 2018. [Online]. Available: https://doi.org/10.1007/s12008-017-0401-4

[216] M. Grieves, "Digital twin: Manufacturing excellence through virtual factory replication," *White paper*, 2014.

[217] F. Tao, H. Zhang, A. Liu, and A. Y. C. Nee, "Digital twin in industry: State-of-the-art," *IEEE Transactions on Industrial Informatics*, vol. 15, pp. 2405–2415, 4 2019. [Online]. Available: https://doi.org/10.1109/TII.2018.2873186

[218] B. R. Barricelli, E. Casiraghi, and D. Fogli, "A Survey on Digital Twin: Definitions, Characteristics, Applications, and Design Implications," *IEEE Access*, vol. 7, pp. 167 653–167 671, 2019. [Online]. Available: https://doi.org/10.1109/ACCESS.2019.2953499

[219] E. J. Tuegel, A. R. Ingraffea, T. G. Eason, and S. M. Spottswood, "Reengineering aircraft structural life prediction using a digital twin," *International Journal of Aerospace Engineering*, vol. 2011, pp. 1–14, 2011. [Online]. Available: https://doi.org/10.1155/2011/154798

[220] W. Kritzinger, M. Karner, G. Traar, J. Henjes, and W. Sihn, "Digital twin in manufacturing: A categorical literature review and classification," *IFAC-PapersOnLine*, vol. 51, pp. 1016–1022, 2018. [Online]. Available: https://doi.org/10.1016/j.ifacol.2018.08.474

[221] C. Lo, C. Chen, and R. Y. Zhong, "A review of digital twin in product design and development," *Advanced Engineering Informatics*, vol. 48, p. 101297, 4 2021. [Online]. Available: https://doi.org/10.1016/j.aei.2021.101297

[222] F. Tao and M. Zhang, "Digital twin shop-floor: A new shop-floor paradigm towards smart manufacturing," *IEEE Access*, vol. 5, pp. 20 418–20 427, 2017. [Online]. Available: https://doi.org/10.1109/ACCESS.2017.2756069

[223] W. Luo, T. Hu, C. Zhang, and Y. Wei, "Digital twin for cnc machine tool: modeling and using strategy," *Journal of Ambient Intelligence and Humanized Computing*, vol. 10, pp. 1129–1140, 3 2019. [Online]. Available: https://doi.org/10.1007/s12652-018-0946-5

[224] P. Aivaliotis, K. Georgoulias, and G. Chryssolouris, "The use of digital twin for predictive maintenance in manufacturing," *International Journal of Computer Integrated Manufacturing*, vol. 32, pp. 1067–1080, 11 2019. [Online]. Available: https://doi.org/10.1080/0951192X.2019.1686173

[225] D. Jones, C. Snider, A. Nassehi, J. Yon, and B. Hicks, "Characterising the digital twin: A systematic literature review," *CIRP Journal of Manufacturing Science and Technology*, vol. 29, pp. 36–52, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1755581720300110

[226] K. M. Alam and A. E. Saddik, "C2ps: A digital twin architecture reference model for the cloud-based cyber-physical systems," *IEEE Access*, vol. 5, pp. 2050–2062, 2017. [Online]. Available: https://doi.org/10.1109/ACCESS.2017.2657006

[227] S. Aheleroff, X. Xu, R. Y. Zhong, and Y. Lu, "Digital twin as a service (dtaas) in industry 4.0: An architecture reference model," *Advanced Engineering Informatics*, vol. 47, p. 101225, 1 2021. [Online]. Available: https://doi.org/10.1016/j.aei.2020.101225

[228] Y. Zheng, S. Yang, and H. Cheng, "An application framework of digital twin and its case study," *Journal of Ambient Intelligence and Humanized Computing*, vol. 10, pp. 1141–1153, 3 2019. [Online]. Available: https://doi.org/10.1007/s12652-018-0911-3

[229] M. Bevilacqua, E. Bottani, F. E. Ciarapica, F. Costantino, L. D. Donato, A. Ferraro, G. Mazzuto, A. Monteriù, G. Nardini, M. Ortenzi, M. Paroncini, M. Pirozzi, M. Prist, E. Quatrini, M. Tronci, and G. Vignali, "Digital twin reference model development to prevent operators' risk in process plants," *Sustainability*, vol. 12, p. 1088, 2 2020. [Online]. Available: https://doi.org/10.3390/su12031088

[230] Q. Qi, F. Tao, T. Hu, N. Anwer, A. Liu, Y. Wei, L. Wang, and A. Nee, "Enabling technologies and tools for digital twin," *Journal of Manufacturing Systems*, vol. 58, pp. 3–21, 1 2021. [Online]. Available: https://doi.org/10.1016/j.jmsy.2019.10.001

[231] G. Shao and M. Helu, "Framework for a digital twin in manufacturing: Scope and requirements," *Manufacturing Letters*, vol. 24, pp. 105–107, apr 2020. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2213846319301312

[232] ISO 23247-2, "Automation systems and integration — digital twin framework for manufacturing — part 2: Reference architecture," 2021.

[233] ISO 23247-3, "Automation systems and integration — digital twin framework for manufacturing — part 3: Digital representation of manufacturing elements," 2021.

[234] ISO 23247-4, "Automation systems and integration – digital twin framework for manufacturing– part 4: Information exchange," 2021.

[235] ISO 23247-5, "Automation systems and integration – digital twin framework for manufacturing– part 5: Digital thread for digital twin," 2024.

[236] G. Shao, "Use case scenarios for digital twin implementation based on iso 23247," *Advanced Manufacturing Series (NIST AMS), National Institute of Standards and Technology*, 5 2021. [Online]. Available: https://doi.org/10.6028/NIST.AMS.400-2

[237] D. B. Kim, G. Shao, and G. Jo, "A digital twin implementation architecture for wire + arc additive manufacturing based on iso 23247," *Manufacturing Letters*, vol. 34, pp. 1–5, 10 2022. [Online]. Available: https://doi.org/10.1016/j.mfglet.2022.08.008

[238] J. V. A. Cabral, E. A. R. Gasca, and A. J. Alvares, "Digital twin implementation for machining center based on iso 23247 standard," *IEEE Latin America Transactions*, vol. 21, pp. 628–635, 5 2023. [Online]. Available: https://doi.org/10.1109/TLA.2023.10130834

[239] B. Wallner, B. Zwölfer, T. Trautner, and F. Bleicher, "Digital twin development and operation of a flexible manufacturing cell using iso 23247," *Procedia CIRP*, vol. 120, pp. 1149–1154, 2023. [Online]. Available: https://doi.org/10.1016/j.procir.2023.09.140

[240] A. Shtofenmakher and G. Shao, “Adaptation of iso 23247 to aerospace digital twin applications-on-orbit collision avoidance and space-based debris detection,” *Aerospace Research Central*, pp. 8–12, 1 2024.

[241] E. Ferko, A. Bucaioni, P. Pelliccione, and M. Behnam, “Standardisation in digital twin architectures in manufacturing,” *2023 IEEE 20th International Conference on Software Architecture (ICSA)*, pp. 70–81, 3 2023. [Online]. Available: https://doi.org/10.1109/ICSA56044.2023.00015

[242] T. DebRoy, W. Zhang, J. Turner, and S. S. Babu, “Building digital twins of 3d printing machines,” *Scripta Materialia*, vol. 135, pp. 119–124, 7 2017. [Online]. Available: https://doi.org/10.1016/j.scriptamat.2016.12.005

[243] G. Knapp, T. Mukherjee, J. Zuback, H. Wei, T. Palmer, A. De, and T. DebRoy, “Building blocks for a digital twin of additive manufacturing,” *Acta Materialia*, vol. 135, pp. 390–399, 8 2017. [Online]. Available: https://doi.org/10.1016/j.actamat.2017.06.039

[244] T. Mukherjee and T. DebRoy, “A digital twin for rapid qualification of 3d printed metallic components,” *Applied Materials Today*, vol. 14, pp. 59–65, 3 2019. [Online]. Available: https://doi.org/10.1016/j.apmt.2018.11.003

[245] L. Zhang, X. Chen, W. Zhou, T. Cheng, L. Chen, Z. Guo, B. Han, and L. Lu, “Digital twins for additive manufacturing: A state-of-the-art review,” *Applied Sciences*, vol. 10, p. 8350, 11 2020. [Online]. Available: https://doi.org/10.3390/app10238350

[246] K. Bartsch, A. Pettke, A. Hübert, J. Lakämper, and F. Lange, “On the digital twin application and the role of artificial intelligence in additive manufacturing: a systematic review,” *Journal of Physics: Materials*, vol. 4, p. 032005, 7 2021. [Online]. Available: https://doi.org/10.1088/2515-7639/abf3cf

[247] D. R. Gunasegaram, A. B. Murphy, M. J. Matthews, and T. DebRoy, “The case for digital twins in metal additive manufacturing,” *Journal of Physics: Materials*, vol. 4, p. 040401, 10 2021. [Online]. Available: https://doi.org/10.1088/2515-7639/ac09fb

[248] A. Gaikwad, R. Yavari, M. Montazeri, K. Cole, L. Bian, and P. Rao, “Toward the digital twin of additive manufacturing: Integrating thermal simulations, sensing, and analytics to detect process faults,” *IISE Transactions*, vol. 52, pp. 1204–1217, 11 2020. [Online]. Available: https://doi.org/10.1080/24725854.2019.1701753

[249] D. Mourtzis, T. Togias, J. Angelopoulos, and P. Stavropoulos, “A digital twin architecture for monitoring and optimization of fused deposition modeling processes,” *Procedia CIRP*, vol. 103, pp. 97–102, 2021. [Online]. Available: https://doi.org/10.1016/j.procir.2021.10.015

[250] P. Stavropoulos, A. Papacharalampoloulos, and K. Tzimanis, "Design and implementation of a digital twin platform for am processes," *Procedia CIRP*, vol. 104, pp. 1722–1727, 2021. [Online]. Available: https://doi.org/10.1016/j.procir.2021.11.290

[251] P. Stavropoulos, A. Papacharalampopoulos, C. K. Michail, and G. Chryssolouris, "Robust additive manufacturing performance through a control oriented digital twin," *Metals*, vol. 11, p. 708, 4 2021. [Online]. Available: https://doi.org/10.3390/met11050708

[252] S. V. Nagar, A. C. Chandrashekar, and M. Suvarna, "Optimized additive manufacturing technology using digital twins and cyber physical systems," *Lecture Notes in Networks and Systems*, vol. 80, pp. 65–73, 2020. [Online]. Available: https://doi.org/10.1007/978-3-030-23162-0_7

[253] P. Nath and S. Mahadevan, "Probabilistic digital twin for additive manufacturing process design and control," *Journal of Mechanical Design*, vol. 144, 9 2022. [Online]. Available: https://doi.org/10.1115/1.4054521

[254] T. Shen and B. Li, "Digital twins in additive manufacturing: a state-of-the-art review," *The International Journal of Advanced Manufacturing Technology*, 2 2024. [Online]. Available: https://doi.org/10.1007/s00170-024-13092-y

[255] Y. Cai, Y. Wang, and M. Burnett, "Using augmented reality to build digital twin for reconfigurable additive manufacturing system," *Journal of Manufacturing Systems*, vol. 56, pp. 598–604, 7 2020. [Online]. Available: https://doi.org/10.1016/j.jmsy.2020.04.005

[256] S. Krückemeier and R. Anderl, "Concept for digital twin based virtual part inspection for additive manufacturing," *Procedia CIRP*, vol. 107, pp. 458–462, 2022. [Online]. Available: https://doi.org/10.1016/j.procir.2022.05.008

[257] C. Mandolla, A. M. Petruzzelli, G. Percoco, and A. Urbinati, "Building a digital twin for additive manufacturing through the exploitation of blockchain: A case analysis of the aircraft industry," *Computers in Industry*, vol. 109, pp. 134–152, 8 2019. [Online]. Available: https://doi.org/10.1016/j.compind.2019.04.011

[258] D. Guo, S. Ling, H. Li, D. Ao, T. Zhang, Y. Rong, and G. Q. Huang, "A framework for personalized production based on digital twin, blockchain and additive manufacturing in the context of industry 4.0," *2020 IEEE 16th International Conference on Automation Science and Engineering (CASE)*, pp. 1181–1186, 8 2020. [Online]. Available: https://doi.org/10.1109/CASE48305.2020.9216732

[259] L. Guo, Y. Cheng, Y. Zhang, Y. Liu, C. Wan, and J. Liang, "Development of cloud-edge collaborative digital twin system for fdm additive manufacturing," *2021 IEEE 19th International Conference on Industrial Informatics (INDIN)*, pp. 1–6, 7 2021. [Online]. Available: https://doi.org/10.1109/INDIN45523.2021.9557492

[260] J. Osho, A. Hyre, M. Pantelidakis, A. Ledford, G. Harris, J. Liu, and K. Mykoniatis, “Four rs framework for the development of a digital twin: The implementation of representation with a fdm manufacturing machine,” *Journal of Manufacturing Systems*, vol. 63, pp. 370–380, 4 2022. [Online]. Available: https://doi.org/10.1016/j.jmsy.2022.04.014

[261] C. Yu and S. Xu, “A digital twin-based augmented reality assisted cloud additive manufacturing framework in support of value co-creation for multi- stakeholder,” *SSRN Electronic Journal*, 2022. [Online]. Available: https://www.ssrn.com/abstract=4210230

[262] C. Liu, L. L. Roux, C. Körner, O. Tabaste, F. Lacan, and S. Bigot, “Digital twin-enabled collaborative data management for metal additive manufacturing systems,” *Journal of Manufacturing Systems*, vol. 62, pp. 857–874, 1 2022. [Online]. Available: https://doi.org/10.1016/j.jmsy.2020.05.010

[263] U. Tariq, R. Joy, S.-H. Wu, M. A. Mahmood, A. W. Malik, and F. Liou, “A state-of-the-art digital factory integrating digital twin for laser additive and subtractive manufacturing processes,” *Rapid Prototyping Journal*, vol. 29, pp. 2061–2097, 11 2023. [Online]. Available: https://doi.org/10.1108/RPJ-03-2023-0113

[264] N. Jyeniskhan, A. Keutayeva, G. Kazbek, M. H. Ali, and E. Shehab, “Integrating machine learning model and digital twin system for additive manufacturing,” *IEEE Access*, vol. 11, pp. 71 113–71 126, 2023. [Online]. Available: https://doi.org/10.1109/ACCESS.2023.3294486

[265] P. Castelló-Pedrero, C. García-Gascón, J. Bas-Bolufer, and J. A. García-Manrique, “Integrated computational modeling of large format additive manufacturing: Developing a digital twin for material extrusion with carbon fiber-reinforced acrylonitrile butadiene styrene,” *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, vol. 238, pp. 332–346, 2 2024. [Online]. Available: https://doi.org/10.1177/14644207231219856

[266] A. Phua, P. S. Cook, C. H. Davies, and G. W. Delaney, “Smart recoating: A digital twin framework for optimisation and control of powder spreading in metal additive manufacturing,” *Journal of Manufacturing Processes*, vol. 99, pp. 382–391, 8 2023. [Online]. Available: https://doi.org/10.1016/j.jmapro.2023.04.062

[267] S. M. Rachmawati, M. A. P. Putra, J. M. Lee, and D. S. Kim, “Digital twin-enabled 3d printer fault detection for smart additive manufacturing,” *Engineering Applications of Artificial Intelligence*, vol. 124, p. 106430, 9 2023. [Online]. Available: https://doi.org/10.1016/j.engappai.2023.106430

[268] R. T. Reisch, L. Janisch, J. Tresselt, T. Kamps, and A. Knoll, “Prescriptive analytics - a smart manufacturing system for first-time-right printing in wire arc additive manufacturing

using a digital twin," *Procedia CIRP*, vol. 118, pp. 759–764, 2023. [Online]. Available: https://doi.org/10.1016/j.procir.2023.06.130

[269] L. Chen, X. Yao, K. Liu, C. Tan, and S. K. Moon, "Multisensor fusion-based digital twin in additive manufacturing for in-situ quality monitoring and defect correction," *Proceedings of the Design Society*, vol. 3, pp. 2755–2764, 7 2023. [Online]. Available: https://doi.org/10.1017/pds.2023.276

[270] M. A. P. Putra, S. M. Rachmawati, R. N. Alief, L. A. C. Ahakonye, A. Gohil, D.-S. Kim, and J.-M. Lee, "Federated learning-enabled digital twin for smart additive manufacturing industry," *2023 International Conference on Artificial Intelligence in Information and Communication (ICAIIC)*, pp. 806–811, 2 2023. [Online]. Available: https://doi.org/10.1109/ICAIIC57133.2023.10067043

[271] G. A. R. Sampedro, M. A. P. Putra, and M. Abisado, "3d-amplifai: An ensemble machine learning approach to digital twin fault monitoring for additive manufacturing in smart factories," *IEEE Access*, vol. 11, pp. 64 128–64 140, 2023. [Online]. Available: https://doi.org/10.1109/ACCESS.2023.3289536

[272] I. 10303-1, "Industrial automation systems and integration — Product data representation and exchange — Part 1: Overview and fundamental principles," *International Standard Organization*, 2024.

[273] M. J. Pratt, "Introduction to iso 10303—the step standard for product data exchange," *Journal of Computing and Information Science in Engineering*, vol. 1, pp. 102–103, 3 2001. [Online]. Available: https://doi.org/10.1115/1.1354995

[274] X. Xu and A. Y. C. Nee, Eds., *Advanced Design and Manufacturing Based on STEP*. Springer London. [Online]. Available: https://doi.org/10.1007/978

[275] I. 10303-11, "Industrial automation systems and integration — Product data representation and exchange — Part 11: Description methods: The EXPRESS language reference manual," *International Standard Organization*, 2004.

[276] I. 10303-21, "Industrial automation systems and integration — Product data representation and exchange — Part 21: Implementation methods: Clear text encoding of the exchange structure," *International Standard Organization*, 2016.

[277] I. 10303-28, "Industrial automation systems and integration — Product data representation and exchange — Part 28: Implementation methods: XML representations of EXPRESS schemas and data, using XML schemas," *International Standard Organization*, 2007.

[278] I. 10303-22, "Industrial automation systems and integration — Product data representation and exchange — Part 22: Implementation methods: Standard data access interface," *International Standard Organization*, 1998.

[279] I. 10303-23, "Industrial automation systems and integration — Product data representation and exchange — Part 23: mplementation methods: C++ language binding to the standard data access interface," *International Standard Organization*, 2000.

[280] I. 10303-24, "Industrial automation systems and integration — Product data representation and exchange — Part 24: Implementation methods: C language binding of standard data access interface," *International Standard Organization*, 2001.

[281] I. 10303-27, "Industrial automation systems and integration — Product data representation and exchange — Part 27: Implementation methods: Java TM programming language binding to the standard data access interface with Internet/Intranet extensions," *International Standard Organization*, 2000.

[282] I. 10303-224, "Industrial automation systems and integration — Product data representation and exchange — Part 224: Application protocol: Mechanical product definition for process planning using machining features," *International Standard Organization*, 2006.

[283] I. 10303-219, "Industrial automation systems and integration — Product data representation and exchange — Part 219: Application protocol: Dimensional inspection information exchange," *International Standard Organization*, 2007.

[284] I. 10303-240, "Industrial automation systems and integration - Product data representation and exchange - Part 240: Application protocol: Process plans for machined products," *International Standard Organization*, 2005.

[285] X. W. Xu, H. Wang, J. Mao, S. T. Newman, T. R. Kramer, F. M. Proctor, and J. L. Michaloski, "STEP-compliant NC research: The search for intelligent CAD/CAPP/CAM/CNC integration," *International Journal of Production Research*, vol. 43, pp. 3703–3743, 2005. [Online]. Available: https://doi.org/10.1080/00207540500137530

[286] T. R. Kramer, F. Proctor, X. Xu, and J. L. Michaloski, "Run-time interpretation of step-nc: implementation and performance," *International Journal of Computer Integrated Manufacturing*, vol. 19, pp. 495–507, 9 2006. [Online]. Available: https://doi.org/10.1080/09511920600622056

[287] I. 14649-10, "Industrial automation systems and integration - Physical device control - Data model for computerized numerical controllers - Part 10: General process data," *International Standard Organization*, 2004.

[288] I. 14649-11, "Industrial automation systems and integration - Physical device control - Data model for computerized numerical controllers - Part 11: Process data for milling," *International Standard Organization*, 2004.

[289] I. 14649-12, "Industrial automation systems and integration - Physical device control - Data model for computerized numerical controllers - Part 12: Process data for turning," *International Standard Organization*, 2005.

[290] I. 14649-13, "Industrial automation systems and integration - Physical device control - Data model for computerized numerical controllers - Part 13: Process data for wire electrical discharge machining (wire-EDM)," *International Standard Organization*, 2013.

[291] I. 14649-14, "Industrial automation systems and integration - Physical device control - Data model for computerized numerical controllers - Part 14: Process data for sink electrical discharge machining (sink-EDM)," *International Standard Organization*, 2013.

[292] I. 14649-111, "Industrial automation systems and integration - Physical device control - Data model for computerized numerical controllers - Part 111: Tools for milling machines," *International Standard Organization*, 2010.

[293] I. 14649-121, "Industrial automation systems and integration - Physical device control - Data model for computerized numerical controllers - Part 121: Tools for turning machines," *International Standard Organization*, 2005.

[294] I. 14649-17, "Industrial automation systems and integration - Physical device control - Data model for computerized numerical controllers - Part 17: Process data for additive manufacturing," *International Standard Organization*, 2020.

[295] AP 238, "ISO 10303-238 STEP-NC Standard - Third Edition," 2022, [Online; Accessed on March 31, 2024]. [Online]. Available: https://ap238.org/ap238e3

[296] F. A. Milaat, P. Witherell, M. Hardwick, H. Yeung, V. Ferrero, L. Monnier, and M. Brown, "STEP-NC Process Planning for Powder Bed Fusion Additive Manufacturing," *Journal of Computing and Information Science in Engineering*, vol. 22, 12 2022. [Online]. Available: https://doi.org/10.1115/1.4055855

[297] STEP Tools Inc., "STEP Python Interface for Digital Twin Manufacturing," 2024, [Online; accessed 04-May-2024]. [Online]. Available: https://pypi.org/project/steptools/

[298] ——, "Make Additive Process Plan," 2024, [Online; accessed 04-May-2024]. [Online]. Available: https://www.steptools.com/docs/stpython/example/make_additive/

[299] P. Carleberg, "Product model driven direct manufacturing," *Solid Free Form Fabrication Symposium*, pp. 270–277, 1994.

[300] C. R. Gilman and S. J. Rock, "The use of step to integrate design and solid freeform fabrication," *International Solid Freeform Fabrication Symposium*, 1995.

[301] V. Kumar and D. Dutta, "An assessment of data formats for layered manufacturing," *Advances in Engineering Software*, vol. 28, pp. 151–164, 4 1997. [Online]. Available: https://doi.org/10.1016/S0965-9978(96)00050-6

[302] D. Dutta, A. Kumar, M. Pratt, and R. D. Sriram, "Towards step-based data transfer in layered manufacturing," *Proceedings of the 10th IFIP WG5.2/5.3 PROLAMAT Conference*, 9 1998.

[303] M. Pratt, A. Bhatt, D. Dutta, K. Lyons, L. Patil, and R. Sriram, "Progress towards an international standard for data transfer in rapid prototyping and layered manufacturing," *Computer-Aided Design*, vol. 34, pp. 1111–1121, 12 2002. [Online]. Available: https://doi.org/10.1016/S0010-4485(01)00189-0

[304] J. J. Haeseong and B.-Y. Lee, "Slicing step-based cad models for cad/rp interface," *International Solid Freeform Fabrication Symposium*, 1999.

[305] E. Rodriguez and A. Alvares, "A step-nc implementation approach for additive manufacturing," *Procedia Manufacturing*, vol. 38, pp. 9–16, 2019. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2351978920300020

[306] E. Rodríguez, R. Bonnard, and A. Alvares, "Avances en el desarrollo de un sistema de manufactura aditiva basado en STEP-NC," *Revista Produção e Desenvolvimento*, vol. 3, pp. 1–16, 2018. [Online]. Available: https://doi.org/10.1007/s40430-019-2039-6

[307] M. Hardwick, Y. F. Zhao, F. M. Proctor, A. Nassehi, X. Xu, S. Venkatesh, D. Odendahl, L. Xu, M. Hedlind, M. Lundgren, L. Maggiano, D. Loffredo, J. Fritz, B. Olsson, J. Garrido, and A. Brail, "A roadmap for step-nc-enabled interoperable manufacturing," *The International Journal of Advanced Manufacturing Technology*, vol. 68, pp. 1023–1037, 9 2013. [Online]. Available: https://doi.org/10.1007/s00170-013-4894-0

[308] X. Xu, "Realization of step-nc enabled machining," *Robotics and Computer-Integrated Manufacturing*, vol. 22, pp. 144–153, 4 2006. [Online]. Available: https://doi.org/10.1016/j.rcim.2005.02.009

[309] G. Zhao, X. Cao, W. Xiao, Q. Liu, and M. B.-G. Jun, "Step-nc feature-oriented high-efficient cnc machining simulation," *The International Journal of Advanced Manufacturing Technology*, vol. 106, pp. 2363–2375, 1 2020. [Online]. Available: https://doi.org/10.1007/s00170-019-04770-3

[310] K. Latif, E. Rodriguez, R. Bonnard, Y. Yusof, and A. Z. A. Kadir, "Expert system to implement step-nc data interface model on cnc machine," *The International Journal of Advanced Manufacturing Technology*, vol. 129, pp. 5371–5385, 12 2023. [Online]. Available: https://doi.org/10.1007/s00170-023-12582-9

[311] S.-H. Suh, D.-H. Chung, B.-E. Lee, S. Shin, I. Choi, and K.-M. Kim, "Step-compliant cnc system for turning: Data model, architecture, and implementation," *Computer-Aided Design*, vol. 38, pp. 677–688, 6 2006. [Online]. Available: https://doi.org/10.1016/j.cad.2006.02.006

[312] S. Habeeb and X. Xu, "A novel cnc system for turning operations based on a high-level data model," *The International Journal of Advanced Manufacturing Technology*, vol. 43, pp. 323–336, 7 2009. [Online]. Available: https://doi.org/10.1007/s00170-008-1718-8

[313] X. Zhang, R. Liu, A. Nassehi, and S. Newman, "A step-compliant process planning system for cnc turning operations," *Robotics and Computer-Integrated Manufacturing*, vol. 27, pp. 349–356, 4 2011. [Online]. Available: https://doi.org/10.1016/j.rcim.2010.07.018

[314] A. Sokolov, J. Richard, V. K. Nguyen, I. Stroud, W. Maeder, and P. Xirouchakis, "Algorithms and an extended step-nc-compliant data model for wire electro discharge machining based on 3d representations," *International Journal of Computer Integrated Manufacturing*, vol. 19, pp. 603–613, 9 2006. [Online]. Available: https://doi.org/10.1080/09511920600634903

[315] S. Zivanovic and R. Puzovic, "Wire edm machining simulations based on step-nc program," *Tehnicki vjesnik - Technical Gazette*, vol. 23, 12 2016. [Online]. Available: https://doi.org/10.17559/TV-20151122180547

[316] F. Ridwan, X. Xu, and G. Liu, "A framework for machining optimisation based on step-nc," *Journal of Intelligent Manufacturing*, vol. 23, pp. 423–441, 6 2012. [Online]. Available: https://doi.org/10.1007/s10845-010-0380-9

[317] H. Wang, R. Y. Zhong, G. Liu, W. Mu, X. Tian, and D. Leng, "An optimization model for energy-efficient machining for sustainable production," *Journal of Cleaner Production*, vol. 232, pp. 1121–1133, 9 2019. [Online]. Available: https://doi.org/10.1016/j.jclepro.2019.05.271

[318] G. Zhao, K. Cheng, W. Wang, Y. Liu, and Z. Dan, "A milling cutting tool selection method for machining features considering energy consumption in the step-nc framework," *The International Journal of Advanced Manufacturing Technology*, vol. 120, pp. 3963–3981, 5 2022. [Online]. Available: https://doi.org/10.1007/s00170-022-08964-0

[319] F. Zhao, X. Xu, and S. Xie, "Step-nc enabled on-line inspection in support of closed-loop machining," *Robotics and Computer-Integrated Manufacturing*, vol. 24, pp. 200–216, 4 2008. [Online]. Available: https://doi.org/10.1016/j.rcim.2006.10.004

[320] C. Danjou, J. L. Duigou, and B. Eynard, "Closed-loop manufacturing process based on step-nc," *International Journal on Interactive Design and Manufacturing*

(IJIDeM), vol. 11, pp. 233–245, 5 2017. [Online]. Available: https://doi.org/10.1007/s12008-015-0268-1

[321] C. Riaño, E. Rodriguez, and A. J. Alvares, "A closed-loop inspection architecture for additive manufacturing based on step standard," *IFAC-PapersOnLine*, vol. 52, pp. 2782–2787, 2019. [Online]. Available: https://doi.org/10.1016/j.ifacol.2019.11.629

[322] S. Zivanovic, N. Slavkovic, and D. Milutinovic, "An approach for applying step-nc in robot machining," *Robotics and Computer-Integrated Manufacturing*, vol. 49, pp. 361–373, 2 2018. [Online]. Available: https://doi.org/10.1016/j.rcim.2017.08.009

[323] J. S. Toquica, S. Zivanovic, R. Bonnard, E. Rodriguez, A. J. Alvares, and J. C. E. Ferreira, "Step-nc-based machining architecture applied to industrial robots," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 41, p. 314, 8 2019. [Online]. Available: https://doi.org/10.1007/s40430-019-1811-y

[324] A. J. Alvares, E. Rodriguez, C. I. R. Jaimes, J. S. Toquica, and J. C. E. Ferreira, "Step-nc architectures for industrial robotic machining: Review, implementation and validation," *IEEE Access*, vol. 8, pp. 152 592–152 610, 2020. [Online]. Available: https://doi.org/10.1109/ACCESS.2020.3017561

[325] P. Hu, J. Li, J. Guo, L. Zhang, and J. Feng, "The architecture, methodology and implementation of step-nc compliant closed-loop robot machining system," *IEEE Access*, vol. 10, pp. 100 408–100 425, 2022. [Online]. Available: https://doi.org/10.1109/ACCESS.2022.3208160

[326] M. S. Ryou, H. S. Jee, W. H. Kwon, and Y. B. Bang, "Development of a data interface for rapid prototyping in step-nc," *International Journal of Computer Integrated Manufacturing*, vol. 19, pp. 614–626, 9 2006. [Online]. Available: https://doi.org/10.1080/09511920600623666

[327] R. Bonnard, P. Mognol, and J.-Y. Hascoët, "A new digital chain for additive manufacturing processes," *Virtual and Physical Prototyping*, vol. 5, pp. 75–88, 2010. [Online]. Available: https://doi.org/10.1080/17452751003696916

[328] R. Bonnard, J.-Y. Hascoët, P. Mognol, and I. Stroud, "Step-nc digital thread for additive manufacturing: data model, implementation and validation," *International Journal of Computer Integrated Manufacturing*, vol. 31, pp. 1141–1160, 11 2018. [Online]. Available: https://doi.org/10.1080/0951192X.2018.1509130

[329] R. Bonnar, P. Mognol, and J.-Y. Hascoët, "Integration of rapid manufacturing processes in a high-level numerical chain," *4th International Conference on Advanced Research in Virtual and Physical Prototyping, VRAP 2009*, pp. 595–601, 10 2009.

[330] R. Bonnard, "An advanced step-nc platform for additive manufacturing," *Industrializing Additive Manufacturing - Proceedings of Additive Manufacturing in Products and Applications - AMPA2017*, pp. 127–136, 2018. [Online]. Available: https://doi.org/10.1007/978-3-319-66866-6_12

[331] M. Rauch, J. Y. Hascoët, V. Simoes, and K. Hamilton, "Advanced programming of machine tools: interests of an open cnc controller within a step-nc environment," *International Journal of Machining and Machinability of Materials*, vol. 15, p. 2, 2014. [Online]. Available: https://doi.org/10.1504/IJMMM.2014.059184

[332] J. Um, M. Rauch, J.-Y. Hascoët, and I. Stroud, "Step-nc compliant process planning of additive manufacturing: remanufacturing," *The International Journal of Advanced Manufacturing Technology*, vol. 88, pp. 1215–1230, 2 2017. [Online]. Available: https://doi.org/10.1007/s00170-016-8791-1

[333] J. Xiao, N. Anwer, A. Durupt, J. L. Duigou, and B. Eynard, "Definition, parameterisation and standardisation of machine-specified data process in additive manufacturing," *Advances in Transdisciplinary Engineering*, vol. 6, pp. 166–171, 9 2017.

[334] J. XIAO, N. ANWER, A. DURUPT, J. L. DUIGOU, and B. EYNARD, "Standardisation focus on process planning and operations management for additive manufacturing," *Lecture Notes in Mechanical Engineering*, pp. 223–232, 2017. [Online]. Available: https://doi.org/10.1007/978-3-319-45781-9_23

[335] J. Xiao, B. Eynard, N. Anwer, A. Durupt, J. L. Duigou, and C. Danjou, "Step/step-nc-compliant manufacturing information of 3d printing for fdm technology," *The International Journal of Advanced Manufacturing Technology*, vol. 112, pp. 1713–1728, 1 2021. [Online]. Available: https://doi.org/10.1007/s00170-020-06539-5

[336] E. Pei, M. Ressin, R. I. Campbell, B. Eynard, and J. Xiao, "Investigating the impact of additive manufacturing data exchange standards for re-distributed manufacturing," *Progress in Additive Manufacturing*, vol. 4, pp. 331–344, 9 2019. [Online]. Available: https://doi.org/10.1007/s40964-019-00085-7

[337] B. N. Lee, E. Pei, and J. Um, "An overview of information technology standardization activities related to additive manufacturing," *Progress in Additive Manufacturing*, vol. 4, pp. 345–354, 9 2019. [Online]. Available: https://doi.org/10.1007/s40964-019-00087-5

[338] E. Rodriguez and A. Alvares, "Implementation of the step-nc and mtconnect standards for additive manufacturing," *10º Congresso Brasileiro de Engenharia de Fabricação*, 2019. [Online]. Available: https://doi.org/10.26678/ABCM.COBEF2019.COF2019-0296

[339] J. Xiao and Y. Lei, “Enriching semantics of geometry features and parameters for additive manufacturing peculiar structure based on step standards,” *Crystals*, vol. 12, p. 1154, 8 2022. [Online]. Available: https://doi.org/10.3390/cryst12081154

[340] J. Um, J. Park, and I. A. Stroud, “Squashed-slice algorithm based on step-nc for multi-material and multi-directional additive processes,” *Applied Sciences*, vol. 11, p. 8292, 9 2021. [Online]. Available: https://doi.org/10.3390/app11188292

[341] F. A. Milaat, P. Witherell, M. Hardwick, and H. Yeung, “Methods for mapping empirical data to authoritative definitions for additive manufacturing part validation,” *Volume 2: 43rd Computers and Information in Engineering Conference (CIE)*, 8 2023. [Online]. Available: https://doi.org/10.1115/DETC2023-116710

[342] K. Latif, Y. Yusof, and A. Z. A. Kadir, “New method to utilize step-nc data interface model for 3d printing,” *Progress in Additive Manufacturing*, vol. 8, pp. 1677–1686, 12 2023. [Online]. Available: https://doi.org/10.1007/s40964-023-00435-6

[343] J. Xiao, N. Anwer, H. Huang, R. Bonnard, B. Eynard, C. Huang, and E. Pei, “Information exchange and knowledge discovery for additive manufacturing digital thread: a comprehensive literature review,” *International Journal of Computer Integrated Manufacturing*, pp. 1–26, 8 2024. [Online]. Available: https://doi.org/10.1080/0951192X.2024.2387768

[344] K. Latif, A. Adam, Y. Yusof, and A. Z. A. Kadir, “A review of g code, step, step-nc, and open architecture control technologies based embedded cnc systems,” *The International Journal of Advanced Manufacturing Technology*, vol. 114, pp. 2549–2566, 6 2021. [Online]. Available: https://doi.org/10.1007/s00170-021-06741-z

[345] S. Suh, B. Lee, D. Chung, and S. Cheon, “Architecture and implementation of a shop-floor programming system for step-compliant cnc,” *Computer-Aided Design*, vol. 35, pp. 1069–1083, 10 2003. [Online]. Available: https://doi.org/10.1016/S0010-4485(02)00179-3

[346] K. Latif, Y. Yusof, A. Z. A. Kadir, R. Bonnard, E. Rodriguez, and N. de Oliveira Pacheco, “New system architecture and algorithm design for indirect step-nc implementation,” *International Journal on Interactive Design and Manufacturing (IJIDeM)*, vol. 17, pp. 1895–1903, 8 2023. [Online]. Available: https://doi.org/10.1007/s12008-023-01317-5

[347] W. Xiao, K. Zhang, S. Wang, J. Xiao, H. Xing, R. Li, and G. Zhao, “Step-nc enabled edge–cloud collaborative manufacturing system for compliant cnc machining,” *Journal of Manufacturing Systems*, vol. 72, pp. 460–474, 2 2024. [Online]. Available: https://doi.org/10.1016/j.jmsy.2023.12.005

[348] STEP Tools, Inc., “STEP Node and .NET API Guide,” 2019, [Online; Accessed on March 31, 2024]. [Online]. Available: https://www.steptools.com/docs/stepnc_api/

[349] B. S. Figueroa, L. Araújo, and A. Alvares, "Development of a digital twin for a laser metal deposition (lmd) additive manufacturing cell," *Advances in Automation and Robotics Research*, pp. 68–76, 2024. [Online]. Available: https://doi.org/10.1007/978-3-031-54763-8_7

[350] J. V. A. Cabral, A. J. Álvares, and G. C. de Carvalho, "Digital twin implementation for an additive manufacturing robotic cell based on the iso 23247 standard," *IEEE Latin America Transactions*, vol. 22, pp. 651–658, 8 2024. [Online]. Available: https://doi.org/10.1109/TLA.2024.10620386

[351] E. Rodriguez, "JSDAI," 1998, [Online; Accessed on March 31, 2024]. [Online]. Available: https://www.jsdai.net/

[352] ——, "STEP-NC on Github: An open-source, extensible, and runtime-friendly Javascript/Typescript library for handling STEP and STEP-NC models." 2023, [Online; Accessed on December 03, 2024]. [Online]. Available: https://github.com/EfrainRodriguez/step-nc

A. APPENDIX

A.1 Journal research publications

The International Journal of Advanced Manufacturing Technology

STEP-NC in Additive Manufacturing: A Comprehensive Review, Architecture and Data Model Proposal

--Manuscript Draft--

Manuscript Number:		
Full Title:	STEP-NC in Additive Manufacturing: A Comprehensive Review, Architecture and Data Model Proposal	
Article Type:	Original Research	
Keywords:	Additive Manufacturing; STEP-NC; ISO 10303-238; Digital Thread; Digital Twin; ISO 23247	
Corresponding Author:	Efrain Rodriguez, Ph.D. University of Brasilia Brasilia, BRAZIL	
Corresponding Author Secondary Information:		
Corresponding Author's Institution:	University of Brasilia	
Corresponding Author's Secondary Institution:		
First Author:	Efrain Rodriguez, Ph.D.	
First Author Secondary Information:		
Order of Authors:	Efrain Rodriguez, Ph.D.	
	Alberto Alvares	
	Cristhian Riaño	
Order of Authors Secondary Information:		
Funding Information:	Fundação de Apoio à Pesquisa do Distrito Federal	Dr. Alberto Alvares
	Conselho Nacional de Desenvolvimento Científico e Tecnológico	Dr. Efrain Rodriguez
Abstract:	In modern manufacturing, Digital Thread and Digital Twin technologies integrate and orchestrate data throughout the production lifecycle. To fully realize their potential, it's crucial to overcome challenges in data integration, management, and interoperability, while enhancing system intelligence and contextual awareness. STEP-NC emerges as a potential solution, enriching digital systems (e.g. Digital Thread and Digital Twins) with contextual information about products, processes, and machines. While STEP-NC has been extensively studied in machining, its application in Additive Manufacturing (AM) is still emerging. Current reliance on legacy formats like STL and G-code fails to meet the industry's advancing needs. This work offers a comprehensive review of the current state of STEP-NC development for AM, highlighting a growing interest in its application, despite limited publications and advancements. To bridge these gaps, we propose STEP-NC entity definitions for managing data related to process parameters and operations in Fused Deposition Modeling (FDM) and Laser Metal Deposition (LMD) technologies. STEP-NC facilitates refined data management at the individual layer level, encompassing geometry, process parameters, material properties, and other key aspects. Additionally, we introduce a comprehensive cyber-physical architecture for STEP-NC in manufacturing, aligned with the ISO 23247 framework. This architecture envisions a robust digital ecosystem driven by standards-based Digital Thread and Digital Twin technologies, with STEP and STEP-NC at its core, supported by essential open standards such as QIF, MTConnect, OPC-UA, and MQTT. By integrating contextual information, it enhances the development of Digital Twins, essential for virtual monitoring, optimization, knowledge generation, and informed decision-making in manufacturing environments.	

Figure A.1: Article 1 (Under Review in IJAMT Journal): STEP-NC in Additive Manufacturing: A Comprehensive Review, Architecture and Data Model Proposal

Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 38 (2019) 9–16

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

29th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2019), June 24-28, 2019, Limerick, Ireland.

A STEP-NC implementation approach for additive manufacturing

Efrain Rodriguez[a,*], Alberto Alvares[a]

[a]*Department of Mechanical and Mechatronics Engineering, University of Brasilia, Brasilia, Brazil*

Abstract

This paper describes an approach for implementing the STEP-NC standard in additive manufacturing. Geometric information of additive manufacturing layers is used as input data to generate the STEP-NC program according to ISO 10303 AP-238. An adapter software was developed to convert the additive layer data into the AP-238 STEP-NC data. Additive STEP-NC program verification is carried out through toolpath simulation within the STEP-NC Machine software environment, including the configuration of the machine's kinematic 3D-model and the tool shape geometry. Validation of the approach is also realized by manufacturing a test part on a real RepRap 3D printer. This method is a feasible way to use STEP-NC in additive manufacturing (3D printing) processes.

Peer-review under responsibility of the scientific committee of the Flexible Automation and Intelligent Manufacturing 2019 (FAIM 2019)

Keywords: additive manufacturing, STEP-NC, interoperability, ISO 10303-238, industry 4.0

1. Introduction

Over the last decade, major advances in information and communication technologies such as Internet of Things (IoT), Cyber-Physical Systems (CPS), Cloud Computing, Artificial Intelligence (AI), Big Data, etc. have significantly reshaped the manufacturing sector and initiated the fourth industrial revolution [1]. This new movement has attracted extensive attention from different governments who have begun to deploy their development plans to take advantage from what it may bring, e.g., ``Industry 4.0" in Germany, 2011; ``Internet Industrial (IIoT)" in the United States, 2012; "Industry 4.0" in European Union, 2014; Japan Industry 4.0 in Japan, 2014; "Made in China 2025" in China, 2015; and "Brazilian Agenda for Industry 4.0" in Brazil, 2017 (http://www.industria40.gov.br/).

* Corresponding author. Tel.: +55 61 98109 9045.
E-mail address: efrainrg2009@gmail.com

Figure A.2: Article 2: A STEP-NC implementation approach for additive manufacturing

Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 52-13 (2019) 2507–2512

Developing a MTConnect Framework for RepRap Additive Manufacturing Machines

Efrain Rodriguez * **Juan Pablo Rodriguez** ** **Alberto J. Alvares** * **Cristhian Riaño** * **Luiz Eduardo de Oliveira** *

* *Department of Mechanical and Mechatronics Engineering, University of Brasilia, Brasilia, Brazil, (e-mail: efrainrg2009@gmail.com, alvares@AlvaresTech.com, cristhianivanrj@gmail.com, luiz.oliveira@unidesc.edu.br)*

** *Department of Mechanical, Mechatronics and Industrial Engineering, University of Pamplona, Pamplona, Colombia, (e-mail: pablo.rodriguez@unipamplona.edu.co)*

Abstract:
The MTConnect standard provides a bridge to bring networked physical manufacturing resources to cloud manufacturing environments. However, making legacy manufacturing equipment compliant with this new standard is still a difficult task. Regarding additive manufacturing machines, this issue has been poorly studied. To address the subject, this work introduces an MTConnect-compliant framework for shopfloor data access and monitoring of RepRap additive manufacturing machines based on Arduino open technology controllers. A communication channel based on TCP/IP protocol using an Ethernet module was incorporated into the machine's system to extend the functionalities of RepRap 3D printers to connect to the Internet. Two MTConnect implementation architectures named Type 1 and Type 2 were proposed. A web-client application was also developed to validate the system by performing real-time machine monitoring over the Internet. The proposed MTConnect solution allows retrieving data of axes position, heat-bed temperature, hot-end temperature, material extrusion, current layer number and elapsed time from the web application, demonstrating feasibility to operate in cloud manufacturing environments.

Keywords: Cloud Manufacturing, MTConnect, Cyber-Physical Systems, Additive Manufacturing

1. INTRODUCTION

The advent of Industry 4.0 is shifting the traditional business models of the manufacturer companies, from production-oriented to service-oriented manufacturing and from mass production to mass customization of products, in order to make them more agile and cost-effective to stay competitive in the global market. Part of this new industrial movement is becoming a reality thanks to the disproportionate growth of technological trends such as cloud manufacturing and additive manufacturing.

The core of cloud manufacturing is, essentially, in the integration of advanced manufacturing systems and cloud computing technologies to enable a pool of networked manufacturing resources and capabilities to be virtualized, encapsulated and provisioned to consumers in a loose-coupled network of on-demand manufacturing services over the Internet (Lu and Xu (2019)). By using cloud and more sustainable production systems (Park and Jeong (2014)).

On the other hand, additive manufacturing is now trusted as the enabling technology with which companies can challenge the heterogeneous and ever-changing user's demands with greater efficiency and high-level of customization (Yao et al. (2017)). Because of its advantages for the creation of three-dimensional objects with complex geometries, multi-material and multicolored, minimizing the waste of material and without needing expensive tools, additive manufacturing becomes convenient for the production of customized products in small batches. Moreover, complex assemblies can now be achieved in a single 3D printed part, reducing manufacturing time and complexity.

Combining additive manufacturing with cloud-based services enables new possibilities to achieve more flexible, intelligent and agile manufacturing systems for mass prod-

Figure A.3: Article 3: Developing a MTConnect Framework for RepRap Additive Manufacturing Machines

Modelo de información para manufactura aditiva basado en STEP-NC

Modelo de informação para fabrico de aditivos baseado em STEP-NC

DOI:10.34117/bjdv8n6-211

Recebimento dos originais: 21/04/2022
Aceitação para publicação: 31/05/2022

Efraín Rodríguez Gasca
Mestre
Institución: Universidade de Brasilia
Dirección: Campus Universitário Darcy Ribeiro, Asa Norte, Brasilia, DF - Brasil
CEP: 70910-900, Caixa Postal: 04386
Correo electrónico: efrainrg2009@gmail.com

Alberto José Álvares
Doutorado
Institución: Universidade de Brasilia
Dirección: Campus Universitário Darcy Ribeiro, Asa Norte, Brasilia, DF - Brasil
CEP: 70910-900, Caixa Postal: 04386
Correo electrónico: alvares@AlvaresTech.com

Renan Bonnard
Doutorado
Institución: (SENAI – SC)
Dirección: (SENAI – SC), Florianópolis - Brazil
Correo electrónico: renan.bonnard@sc.senai.br

RESUMEN
El nuevo estándar de control numérico ISO 14649 e ISO 10303-238, conocido informalmente como STEP-NC, es ahora categorizado como el futuro de los sistemas avanzados de manufactura. STEP-NC es pensado para una nueva gama de contoladores numéricos más inteligentes, flexibles e interoperables. Este nuevo estándar ha sido parcialmente desarrollado para los procesos de mecanizado (fresado, torneado, etc.). Sin embargo, en Manufactura Aditiva (AM) con STEP-NC el desarrollo es aún incipiente. En este contexo, el presente trabajo propone una extensión del modelo de información de STEP-NC para AM y resalta las ventajas de tal modelo. Se presenta un modelo de actividades de aplicación utilizando la nomenclatura IDEF0 para describir globalmente el modelo. Se introduce el concepto de AM-layer-feature para referenciar cada capa del modelo 3D rebanado de la parte como una feature de AM. Entonces, un modelo de referencia de aplicación en EXPRESS también es presentado. Finalmente, a parir del modelo en EXPRESS es generado un archivo de programa en STEP-NC, el cual puede ser implementado sobre un sistema de AM.

Palabras clave: ISO 10303-238, ISO 14949, manufactura aditiva, STEP-NC.

RESUMO
A nova norma de controlo numérico ISO 14649 e ISO 10303-238, informalmente conhecida como STEP-NC, é agora categorizada como o futuro dos sistemas avançados

Figure A.4: Article 4: Modelo de información para manufactura aditiva basado en STEP-NC

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2020.3017561, IEEE Access

IEEE Access

Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2020.DOI

STEP-NC Architectures for Industrial Robotic Machining: Review, Implementation and Validation

ALBERTO J. ÁLVARES[1], EFRAIN RODRIGUEZ[1], CRISTHIAN I. R. JAIMES[1], JUAN S. TOQUICA[1] and JOÃO C. E. FERREIRA[2]

[1]Department of Mechanical Engineering, University of Brasilia, Brasilia, Brazil.

[2]Department of Mechanical Engineering, Federal University of Santa Catarina, Florianópolis, Brazil

Corresponding author: Efrain Rodriguez (e-mail: efrainrg2009@gmail.com)

This study was financed in part by the "Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil" (CAPES) – Finance Code 001. The authors would also like to thank the University of Brasilia, MEC, CNPq and FAPDF for supporting this research.

ABSTRACT In the manufacturing sector, industrial robots are being increasingly improved to execute machining tasks as they exhibit significant advantages in terms of flexibility, cost-effectiveness, affordability, and larger work-space when compared to traditional computer numeric control (CNC) machines. However, programming this kind of equipment for robotic machining is complex, due to closed architecture controller and proprietary programming languages limitations. For that reason, this work aims at contributing to the adoption of the STEP-NC standard (STandard for the Exchange of Product model data- Numerical Control (ISO 10303-238 and ISO 14649)), generating programs for robotic machining operations. The STEP-NC data model enables the integration of information from design, process planning, simulation, manufacturing, and even inspection in a single platform, which could create new alternatives for industrial robotic machining programming. In this context, several previous studies are described in this manuscript aiming to highlight the contribution of this work, in addition to the analysis, implementation, and validation of six different STEP-NC architectures describing the advantages that each architecture provides for achieving robotic machining capabilities. Each introduced architecture can successfully generate a STEP-NC robotic machining program, either as ISO 10303-238 or ISO 14649, which are validated in a simulation environment with both a virtual robot model and a real industrial robot equipped with a LinuxCNC controller. This approach can be implemented in different industrial robots.

INDEX TERMS Computer Numerical Control, Data Modelling, ISO 10303 AP238, LinuxCNC controller, Robotic Machining, STEP-NC Standard.

I. INTRODUCTION

INDUSTRIAL robots have been generally applied in tasks such as painting, packaging, welding, and pick-and-place operations. In the last few years they have been increasingly used to perform machining tasks as well. Compared with traditional machine tools, industrial robots provide significant advantages in terms of flexibility, cost-effectiveness, affordability, and larger work-space. Furthermore, robots can allow new machining strategies for highly complex parts since they have more degrees of freedom than conventional machine tools. However, one of the substantial limitations that hinder the widespread adoption of industrial robots is their low stiffness, mainly in machining with high material removal rates [1]–[4]. In this context, a significant amount of research on robotic machining has been done over the past decades, and a review of some of those works was presented in [3].

An additional problem related to the use of robots in machining is the difficulty to integrate robotic systems present in the factory's numerical chain, since most robots tend to use closed architecture controllers and proprietary programming languages. This problem has motivated industry leaders to implement more efficient and standardized programming methods towards production approaches such as smart manufacturing [5]. In this context, STEP-NC emerges as a new CNC programming standard that provides means to integrate

Figure A.5: Article 5: STEP-NC Architectures for Industrial Robotic Machining: Review, Implementation and Validation

Digital Twin Implementation for Machining Center Based on ISO 23247 Standard

João V. A. Cabral, Efrain Rodriguez, and Alberto J. Alvares

Abstract—**In the context of the Industry 4.0, Digital Twins are essential tools for monitoring and controlling manufacturing processes. In this sense, this work presents the development and implementation of a Digital Twins architecture for machining using a CNC Haas Mini Mill machine. The proposed architecture is based on the current Digital Twins framework for manufacturing normalized by ISO 23247. MQTT and MTConnect protocols are used to transfer machine status and process data to cloud platforms for realizing storing, monitoring, visualization, and simulation activities. This approach was validated in a real CNC machine and it is feasible to be applied to other machines and manufacturing processes.**

Index Terms—**Digital Twins, MTConnect, MQTT, ISO 23247, Industry 4.0.**

I. Introdução

A partir de 2011, tecnologias disruptivas como Internet das Coisas (IoT-*Internet of Things*), Inteligência Artificial (AI - *Artificial Intelligence*), Computação na Nuvem (Cloud Computing) e Dados Massivos (Big Data / Analytics) ganharam espaço no campo da manufatura para propiciar uma nova revolução industrial, referida como Indústria 4.0 [1]. Um dos propósitos da Indústria 4.0 é transformar os sistemas de produção industrializados atuais em direção a uma nova geração de sistemas de produção baseados em sistemas ciber-físicos (CPS - *Cyber-Physical Systems*) [2], [3].

Os CPPS [2] constituem a materialização dos sistemas ciber-físicos (CPS - Cyber-Physical Systems) no ambiente de manufatura; eles são caracterizados pela integração de máquinas-ferramenta, processos de manufatura e tecnologia de redes, onde os processos e operações de produção podem ser monitorados e controlados nestes espaços computacionais ao mesmo tempo que criam ciclos de retroalimentação para afetar as computações e vice-versa [3].

Os Gêmeos Digitais (DT - *Digital Twins*) são o núcleo tecnológico de todo CPS [4]. DT representam a virtualização de entidades físicas de manufatura alimentada por dados coletados em tempo real, permitindo otimização em malha fechada para alterar o comportamento de ditas entidades e processos físicos. A tecnologia de DT vem ganhando cada vez mais relevância tanto no âmbito acadêmico quanto no setor industrial [4], [5].

Enquanto isso, as máquinas-ferramenta continuam tendo um papel fundamental dentro de qualquer ambiente de manufatura, sendo que a produtividade dos processos e qualidade final do produtos fabricados depende em grande medida de sua eficiência e capacidade. O conceito de máquina-ferramenta ciber-física comandada por tecnologia de DT tem sido introduzido por [3], onde as máquinas-ferramenta deveriam ser mais inteligentes, autônomas, adaptáveis, flexíveis e com capacidades *smart*. Com a ideia de alcançar o próximo nível tecnológico das máquinas-ferramenta baseadas em DT é necessário impulsar e acelerar o desenvolvimento de implementações que levem a resolver questões como: que arquitetura/framework de implementação de DT pode ser usada? Quais protocolos de comunicação são factíveis para coleta de dados em tempo real? Que tecnologias podem ser selecionadas para construção de DT visando aplicações de manufatura?

Nesse sentido, o trabalho responde a essas questões e apresenta uma implementação de DT para processos de usinagem usando um centro de usinagem vertical CNC Haas Mini Mill com interface de comunicação RS232. Uma aplicação de servidor suportando os protocolos de comunicação MTConnect e MQTT foi desenvolvida para coletar os dados de máquina no chão de fábrica e disponibilizá-los via API para um cliente web. Neste caso, o objetivo principal foi usar os dados de máquina coletados em tempo real para alimentar um ambiente de simulação WebGL (Web Graphics Library) com o modelo 3D da máquina Haas, ferramenta de corte e da peça sendo usinada. Um dashboard de monitoramento com capacidade de armazenamento de dados na nuvem da IBM é também apresentado.

O trabalho é organizado da seguinte forma: a seção II apresenta uma breve revisão de literatura sobre os principais modelos de referência e arquiteturas de implementação de DT e listando os principais trabalhos correlatos encontrados; a seção III descreve a arquitetura de implementação proposta com base no framework da norma ISO 23247; a seção IV descreve os detalhes de implementação e ressalta os principais resultados obtidos; finalmente, as principais conclusões do trabalho são ressaltadas.

II. Revisão de Literatura

Uma das definições de DT mais bem aceitas pela comunidade científica foi introduzida pela NASA em 2012, onde definem o *Digital Twin* como "uma simulação integrada, multi-física, multi-escalar e probabilística de um veículo ou sistema construído, que utiliza os melhores modelos físicos disponíveis, atualizações de sensores, histórico, etc., para espelhar a vida da correspondente contra-parte" [6].

Algumas propostas de modelos de referência e frameworks de arquitetura para implementação de DT em manufatura, bem como, de trabalhos correlatos são apresentados a seguir.

João V. A. Cabral, Efrain Rodriguez and Alberto J. Alvares are with Department of Mechanical Engineering, University of Brasilia, Brazil, e-mails: jvarantescabraltrab@gmail.com, efrainrg2009@gmail.com, alvares@AlvaresTech.com

Figure A.6: Article 6: Digital Twin Implementation for Machining Center Based on ISO 23247 Standard

The International Journal of Advanced Manufacturing Technology (2023) 129:5371–5385
https://doi.org/10.1007/s00170-023-12582-9

ORIGINAL ARTICLE

Expert system to implement STEP-NC data interface model on CNC machine

Kamran Latif[1] · Efrain Rodriguez[2] · Renan Bonnard[3] · Yusri Yusof[4] · Aini Zuhra Abdul Kadir[5]

Received: 12 March 2023 / Accepted: 22 October 2023 / Published online: 18 November 2023

Abstract
One of the issues in manufacturing is implementing the standard for the exchange of product data-numerical control (STEP-NC) data interface model on computer numeric control (CNC) machines. The most often used STEP-NC programming techniques for this implementation are indirect, interpreted, and adaptive. Because of the ease of integration with existing control systems, the performance of the interpreted method was noticeably superior to that of the indirect and adaptive approaches. This concept has resulted in the creation of several tools, systems, designs, algorithms, and methods. In this study, a new STEP-NC implementation system has been created, in which the interpretation has been done using entity-plus string-based (double layer) for more precise data extractions, the tool paths system can create facing, pocket, drill, bore, ream, countersink, side, slot, and contour operations, the output file generation system can create output as per interpreted and hybrid programming approaches, and the execution system can handle multi-threaded operations. To enhance the overall interpretation system and automate implementation by reducing manual intervention, an expert system has also been incorporated. The STEP-NC part 21 examples 1 and 2 part programs were manufactured on the CNC prototype to validate the technology. The creation of the system, the design of the algorithm, the experimental verification, the conclusion, and the future suggestions are described in the paper's content.

Keywords STEP-NC · ISO 14649 · STEP-NC implementation · CNC expert system

1 Introduction

The CNC unit's ability to generate, parse, and execute sequential control has made it an indispensable part of the production process ever since its inception. The usage of personal computers and CAD/CAM programs is crucial to this innovation. It has seen extensive use across many different sectors, each employing its unique controller and implementation strategy. There was a rise in the 1970s and 1980s in the need for CNC systems to be flexible. Since CNC machines can be easily re-programmed to manufacture a wide variety of components, they have become an invaluable tool for gaining insight into the current state of modular manufacturing [1]. Scalable CNC systems' development did reveal some shortcomings in the ISO 6983 data interface model, such as the following: providing limited data to CNC, shifting one-way communication from CAD/CAM to CNC, being unable to incorporate smooth convergence between CAD-CAM-CNC, having extremely large and difficult to manage programs, and having difficulty accommodating last-minute changes on the shop floor [2]. Over the years, many manufacturers have extended G codes with new supplementary commands to provide new features to their systems. These augmentations are not part of ISO 6983. As a result, G code becomes more machine-specific due to the component programs' effect on computer interoperability [1].

In order to address these concerns, ISO 10303, or the standard for the exchange of product data, was developed in 1994, revised in 2021, and will be replaced with ISO/DIS 10303-1 [3]. This standard aims to offer an open-source methodology for characterizing commodity data at all stages of its existence. The information interchange between CNC machines and CAM systems has been facilitated by ISO 10303, which also increased interoperability between CAD devices. To bring the advantages of STEP to CAM and CNC, the International Organization for Standardization (ISO)

✉ Kamran Latif
kamran@ftv.upsi.edu.my; engr.kamranqureshi@gmail.com

Extended author information available on the last page of the article

Figure A.7: Article 7: Expert system to implement STEP-NC data interface model on CNC machine

Available online at www.sciencedirect.com

ScienceDirect

IFAC Papers Online
CONFERENCE PAPER ARCHIVE

IFAC PapersOnLine 52-13 (2019) 2782–2787

A Closed-Loop Inspection Architecture for Additive Manufacturing Based on STEP Standard

Cristhian Riaño * Efrain Rodriguez * Alberto J. Alvares *

* *Department of Mechanical and Mechatronics Engineering, University of Brasilia, Brasilia, Brazil, (e-mail: cristhian.riano@unb.br, efrainrg2009@gmail.com, alvares@AlvaresTech.com).*

Abstract:
Among the challenges posed by the new industrial revolution-Industry 4.0 is the integration of systems associated with manufacturing. In this sense, the inspection process assumes an important role since it provides the information base to make the decisions that allow reaching the design and quality specifications. From the manufacturing point of view, Additive Manufacturing (AM) contains the potential to meet production demands by making efficient use of resources, reducing manufacturing time, and enabling the manufacture of complex parts. The idea of integrating the inspection process with a robotic system for additive manufacturing seeks both to improve the quality of the parts produced and to find methods to optimize the process and create a sustainable system. However, to make this combination a reality, it is necessary to face the barriers posed by the lack of integration of the information produced by the different computerized systems throughout the life cycle of the product. Thus, there is no integration of feedback information from shop-floor necessary for inspection and validation of the part manufactured with AM, which does not allow a closed-loop digital thread. Concerning this, the present article proposes the development of an integration strategy with a digital data model based on STEP-NC (Standard for the Exchange of Product model data - Numerical Control) for closed-loop AM. The data models in STEP-NC for the AM and inspection tasks it develops, highlighting the scenario of integrated feedback for the closed-loop AM digital thread. Are presented the architecture of integration validated by using an open AM platform and the results of error control over the parts.

Keywords: Closed-loop inspection, Quality management, Additive manufacturing, Interoperability, ISO 10303, STEP-NC

1. INTRODUCTION

Within the perspective of the fourth industrial revolution, the concept of intelligent manufacturing it is associated with processes operating in cooperative and fully integrated environments through digital technologies that offer useful real-time information to learn and improve working conditions (Bortolini et al. (2018)). The objective of the manufacturing industry is to meet production demands by efficiently using available resources to improve performance and achieve more sustainable processes (Lu and Xu (2019)). Within this trend, new challenges that seek to insert avant-garde technologies to accomplish this goal are constantly renewed (Xu et al. (2018)).

The additive manufacturing due to significant progress in matters of speed, quality, and flexibility in the manufacture of parts is considered a mega-trend from Industry 4.0

this technology thanks to the inclusion of new materials (Lasi et al. (2014)).

The multiple factors that need control in the production of a part utilizing additive manufacturing (temperature, speed, material) produce uncertainty in the results that affect the final quality of the parts produced (Qin et al. (2017)). Considering the context of expansion that is evident where quality factors are decisive, the search for a strategy that manages to identify manufacturing errors and compensate within the manufacturing chain will solve some quality issues that prevent consolidation in sectors with precise requirements in these aspects (Zheng et al. (2018)).

Dimensional inspection used as a tool for verification and validation of the specifications of a product plays an essential role in the search for an interoperable manufacturing environment (Moroni and Petrò (2018)). Through the

Figure A.8: Article 8: A Closed-Loop Inspection Architecture for Additive Manufacturing Based on STEP Standard

International Journal on Interactive Design and Manufacturing (IJIDeM) (2023) 17:1895–1903
https://doi.org/10.1007/s12008-023-01317-5

ORIGINAL PAPER

New system architecture and algorithm design for indirect STEP-NC implementation

Kamran Latif[1] · Yusri Yusof[2] · Aini Zuhra Abdul Kadir[3] · Renan Bonnard[4] · Efrain Rodriguez[5] · Nazareno de Oliveira Pacheco[6]

Received: 21 July 2022 / Accepted: 23 February 2023 / Published online: 11 April 2023

Abstract

The adoption of STEP-NC on CNC machines has been one of the most enduring difficulties in daily operations. It is not outside of the realm of possibility to put this solution into practice by techniques that are indirect, interpretative, or adaptive. In this implementation, the interpreted approach's performance was noticeably better than the indirect method's. In this particular field, a substantial amount of investigation still needs to be carried out. This investigation focuses on a better interpreted STEP-NC programming paradigm, and a novel data interpretation approach along with algorithm design are presented. The system has been contributed with the latest hybrid method, which combines the indirect and interpreted strategies for constructing tool paths. In addition, the interpretation algorithm has been updated to incorporate a method for extracting data in two layers (entity and string). The entirety of the system is made up of a variety of software tools and algorithms for the purpose of data extraction, tool path development, and execution. The information included in the paper explains the system's structure and the process used to construct the algorithm. In addition, it has been tested on the STEP-NC part 21 examples 1 and 2.

Keywords STEP-NC · ISO 14649 · Interpretation · CNC

1 Introduction

It is common knowledge in the world of manufacturing that a standard called the Standard for the Exchange of Product Data-Numeric Control (STEP-NC) was developed and implemented. It was developed in response to problems with the ISO 6983 data interface concept, which prompted its introduction. The Standard for the Exchange of Product Data (STEP) served as the foundation for the development, which was later augmented to include STEP-NC for machine execution. The STEP-NC data model's structure may be broken down into two distinct sections: the HEADER part and the DATA section. The HEADER contains essential data, such as the file's name, creator, the current date, and the organization. Whereas the other component, referred to as DATA, includes all the data about manufacturing jobs and geometries. The contents of this section are further separated into three parts: a work plan, a description of the technology, and a description of the geometry. A succession of manufacturing tasks or commands is outlined in the work plan in the order in which they are to be completed. There is a possibility that this component will also include information regarding the workpiece. The executables can be divided

✉ Kamran Latif
kamran@ftv.upsi.edu.my ; engr.kamranqureshi@gmail.com

Yusri Yusof
yusri@uthm.edu.my

Aini Zuhra Abdul Kadir
aini@mail.fkm.utm.my

Renan Bonnard
renan.bonnard@gmail.com

Efrain Rodriguez
efrainrg2009@gmail.com

Nazareno de Oliveira Pacheco
nazareno.pacheco@edu.sc.senai.br

1 Department of Engineering Technology, Fakulti Teknikal Dan Vokasional,Universiti Pendidikan Sultan Idris (UPSI), Tanjung Malim, Malaysia

2 Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), Parit Raja, Malaysia

3 School of Mechanical Engineering, Faculty of Engineering, Universiti Tecknologi Malaysia (UTM), Johor Bahru, Malaysia

4 Senai Innovation Institute For Embedded Systems, Senai, Brazil

Figure A.9: Article 9: New system architecture and algorithm design for indirect STEP-NC implementation

Journal of the Brazilian Society of Mechanical Sciences and Engineering (2019) 41:314
https://doi.org/10.1007/s40430-019-1811-y

TECHNICAL PAPER

STEP-NC-based machining architecture applied to industrial robots

Juan S. Toquica[1] · Sasa Zivanovic[3] · Renan Bonnard[2] · Efrain Rodriguez[1] · Alberto J. Alvares[1] · João C. E. Ferreira[4]

Received: 4 December 2018 / Accepted: 27 June 2019

Abstract

This paper presents a method for applying the ISO 10303-238 (AP-238) standard in robotic machining operations by using two industrial robots. The method encompasses programming, simulation and machining by industrial robots. Application and validation of robotized machining is performed using two industrial robots, and the following tools are used: (a) a commercial CAD/CAM software with a plug-in to generate STEP-NC files (AP-238); (b) simulation with a STEP-NC-compliant software using two virtual robot models, as well as the generation of G-code files through postprocessors; and (c) two industrial robots (ASEA IRB6-S2 and LOLA 50) using the LinuxCNC controller adapted to STEP-NC. Initially, a 3D part is designed using any CAD system, and it is sent through the Internet to a CAM specialist who uses a commercial software to generate a process plan to manufacture the part. Operators of the robots download the part and its process plan information in the STEP-NC format, simulate its machining through the working steps and then perform machining using the robots.

Keywords STEP-NC · AP-238 · LinuxCNC · Industrial robots · Machining

1 Introduction

With the necessity of competitive advanced manufacturing in the context of Industry 4.0 concepts [1], robotics for manufacturing tasks [2] is a major challenge. Indeed, industrial robots are very interesting solutions for on-demand production, mass customization as well as shortened product life cycles with more flexibility [3]. Zivanovic et al. [4] argued that compared to machine tools, industrial robots are cheaper and more flexible with a potentially larger workspace. This interest in applying robotics in machining is also explained by the fact that robot stiffness has been improved, leading to stiffer and stronger structures [5].

In this context, there is a need to develop robot off-line programming systems based on a suitable complete computer-aided design (CAD)/computer-aided manufacturing (CAM) solution and on the development of low-cost and advanced computerized numerical control (CNC) for industrial robots, in order to ensure the competitiveness of these solutions.

In order to contribute to solving the interoperable problem in the manufacturing digital chain, the STEP-NC standard has been developed. This standard benefits the international effort of industry and academia in the ISO committees, which develops ISO 14649 [6] and ISO 10303-238 standards [7]. Many researches have led to the development of

Technical Editor: Victor Juliano De Negri, D.Eng..

✉ Juan S. Toquica
jstoquica@gmail.com

Sasa Zivanovic
szivanovic@mas.bg.ac.rs

Renan Bonnard
renan.bonnard@gmail.com

Efrain Rodriguez
efrainrg2009@gmail.com

Alberto J. Alvares
alvares@AlvaresTech.com

João C. E. Ferreira
jcarlos.ferreira@gmail.com

1 Mechanic and Mechatronic Engineering Department, University of Brasilia, Brasília, DF, Brazil

2 SENAI/SC Innovation Institute for Laser Manufacturing, Manufacturing Systems and Embedded Systems, Florianópolis, Brazil

3 Faculty of Mechanical Engineering, University of Belgrade, Belgrade, Serbia

4 Mechanical Engineering Department, Federal University of Santa Catarina, Florianópolis, Brazil

Published online: 10 July 2019 Springer

Figure A.10: Article 10: STEP-NC-based machining architecture applied to industrial robots

B. APPENDIX

B.1 Guide: how to use the stepnc.dll to generate STEP-NC programs

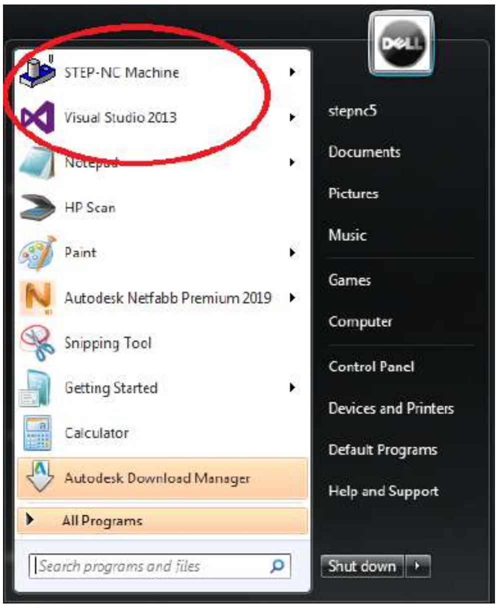
Generating a trivial STEP-NC program file - C++.

Contributor: Efrain Rodriguez

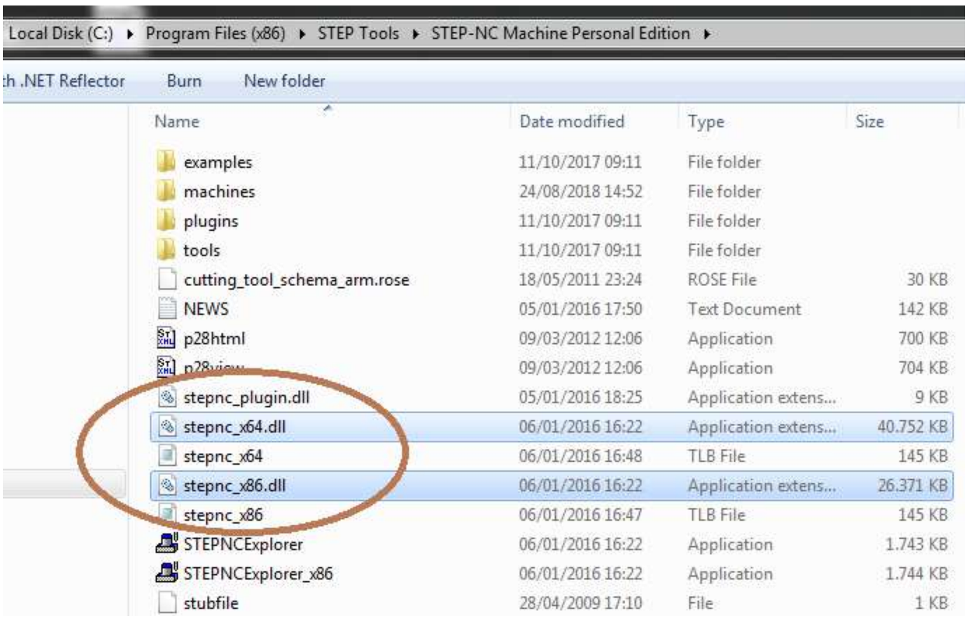
STEP-NC LaDPRER

This is a tutorial version of the "stepnc-hello" demo shared by STEP Tools, Inc. for building a trivial STEP-NC program file. This consists of a small code project written in C++ that creates a machining program as STEP-NC.

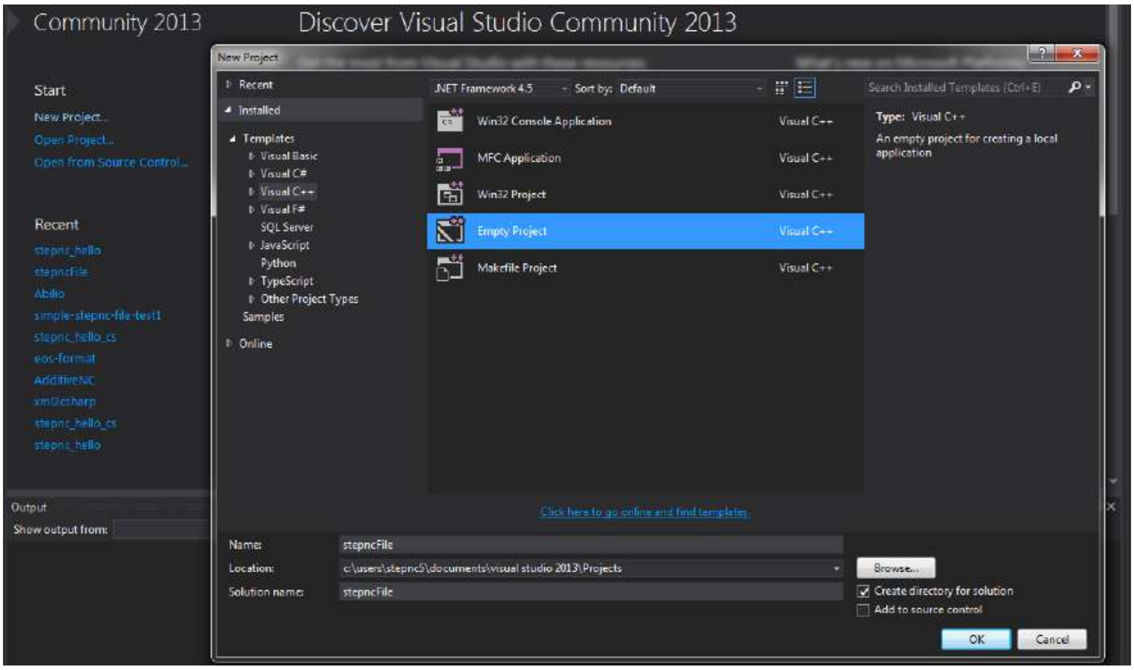
You need **Visual Studio 2013** installed on your **Windows** operating system. You also need the **STEP-NC Machine** software containing the **stepnc.dll** to create the STEP-NC data.



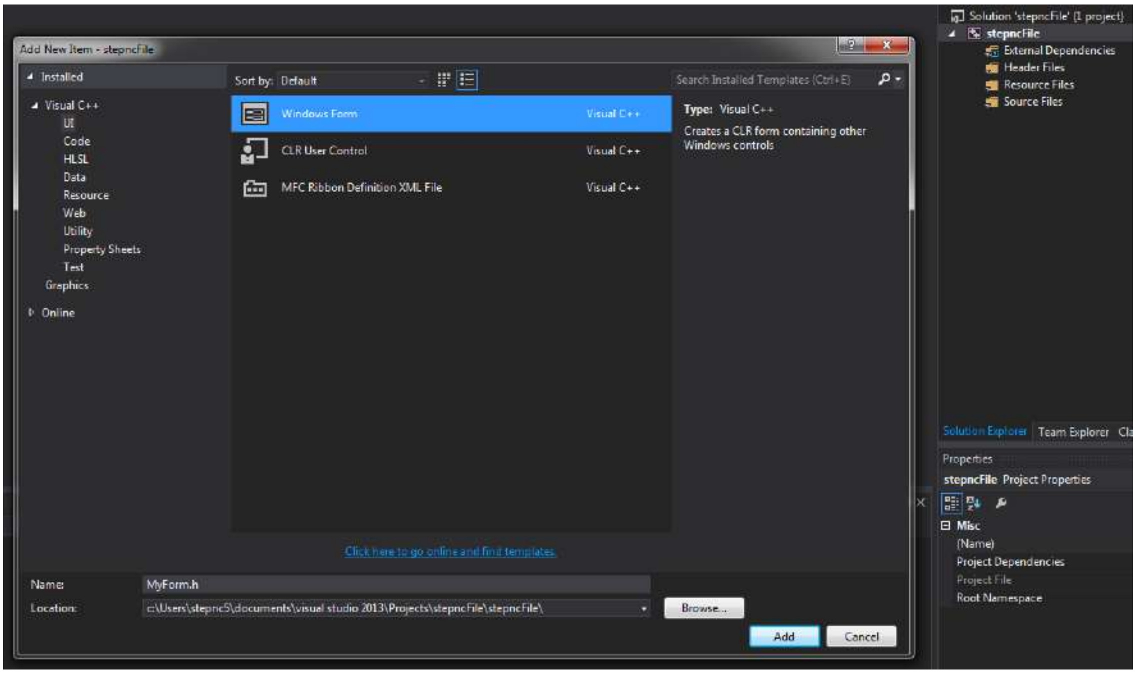
Make sure that the **stepnc_x64.dll** and/or **stepnc_x86.dll** are installed in the STEP-NC Machine directory, usually: **C:\Program Files (x86)\STEP Tools\STEP-NC Machine Personal Edition.**



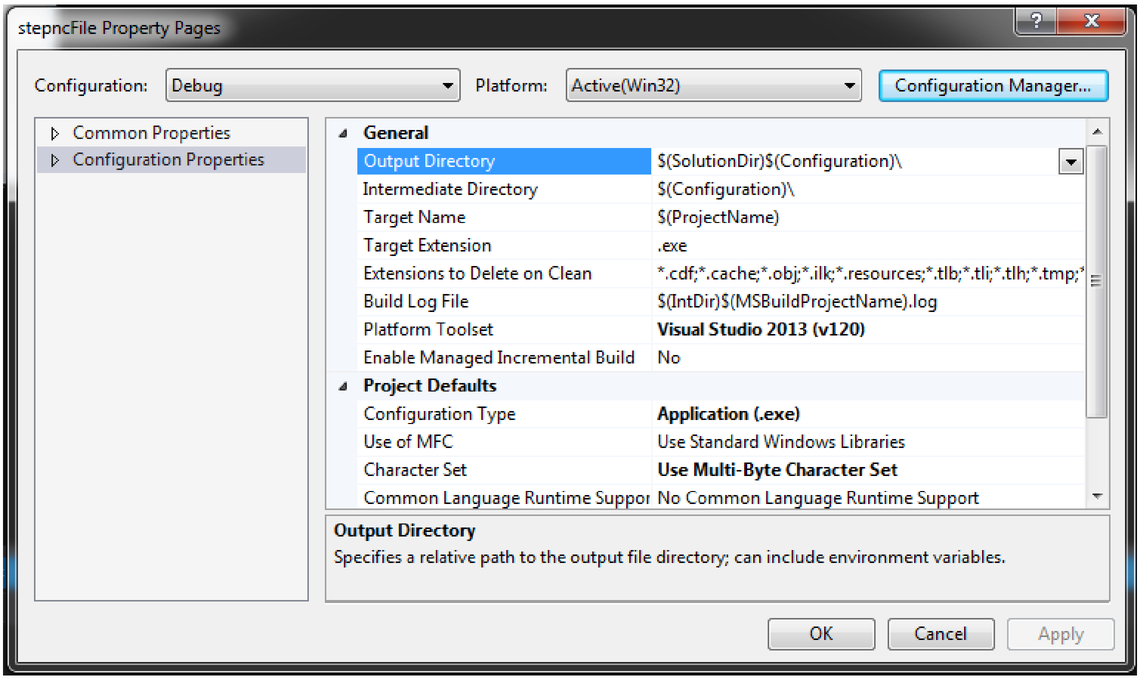
You will need to create a new C++ **Empty Project** by starting Visual Studio. Give your project a name; for example, “stepncFile”.



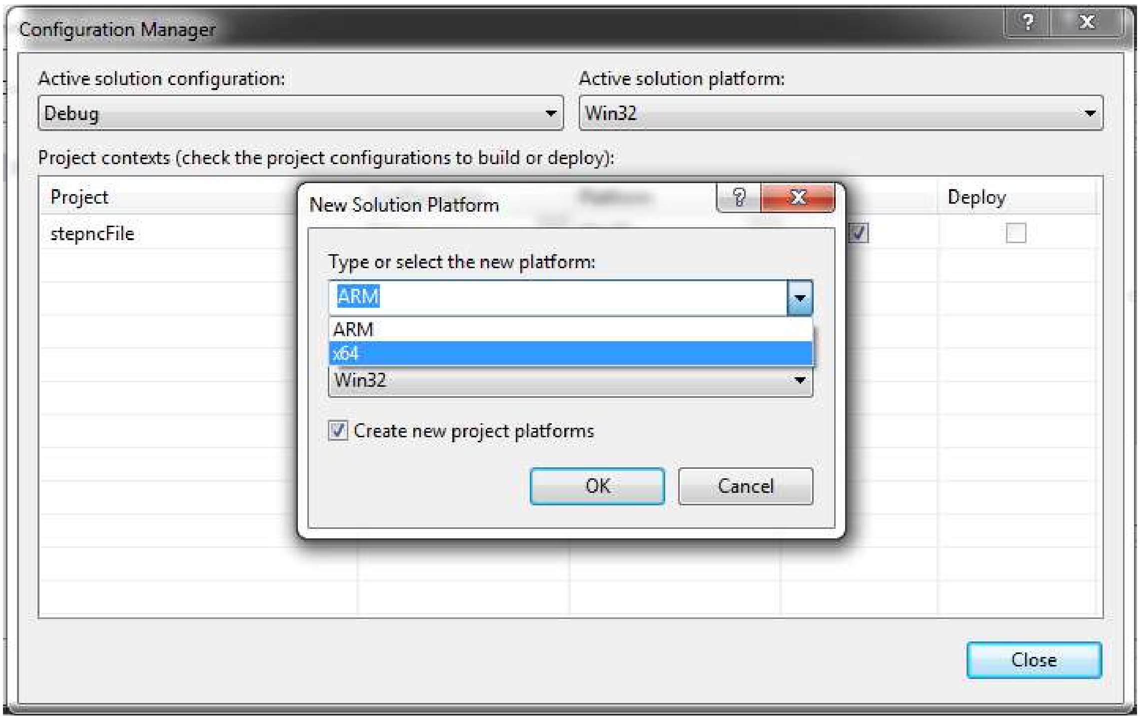
Then add a new **Windows Form** item and give it the name you want; for example, “MyForm”.



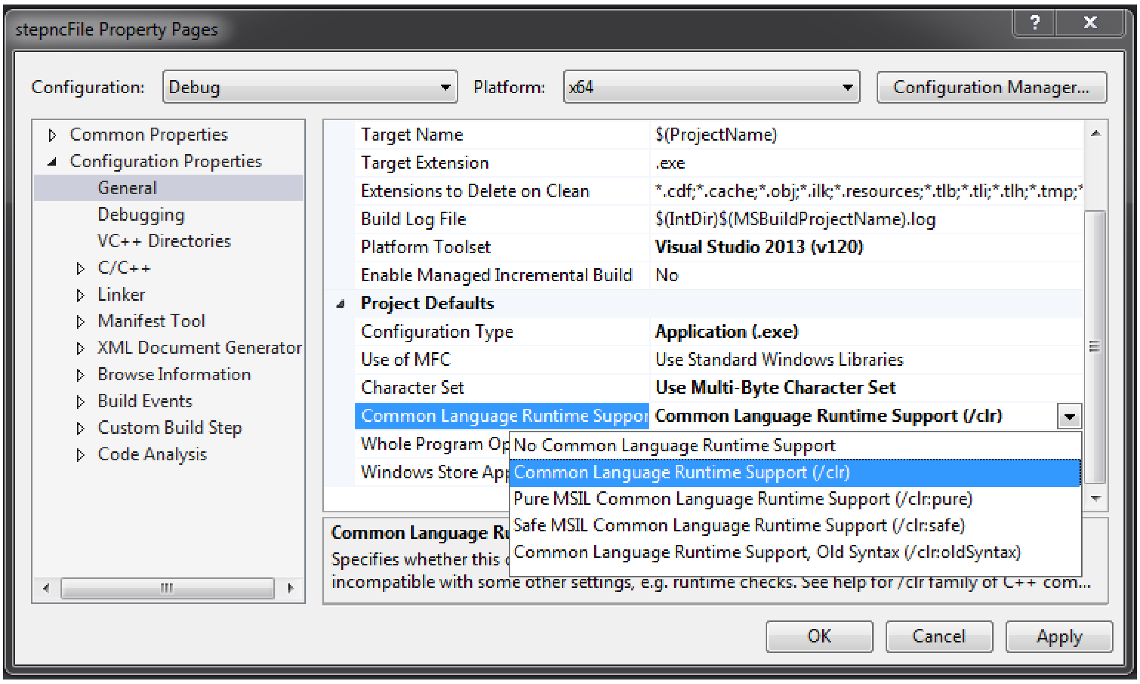
By right clicking on the project, select **Properties** from the menu that will appear to open the project **Property Pages**. Then click on **Configuration Manager**.



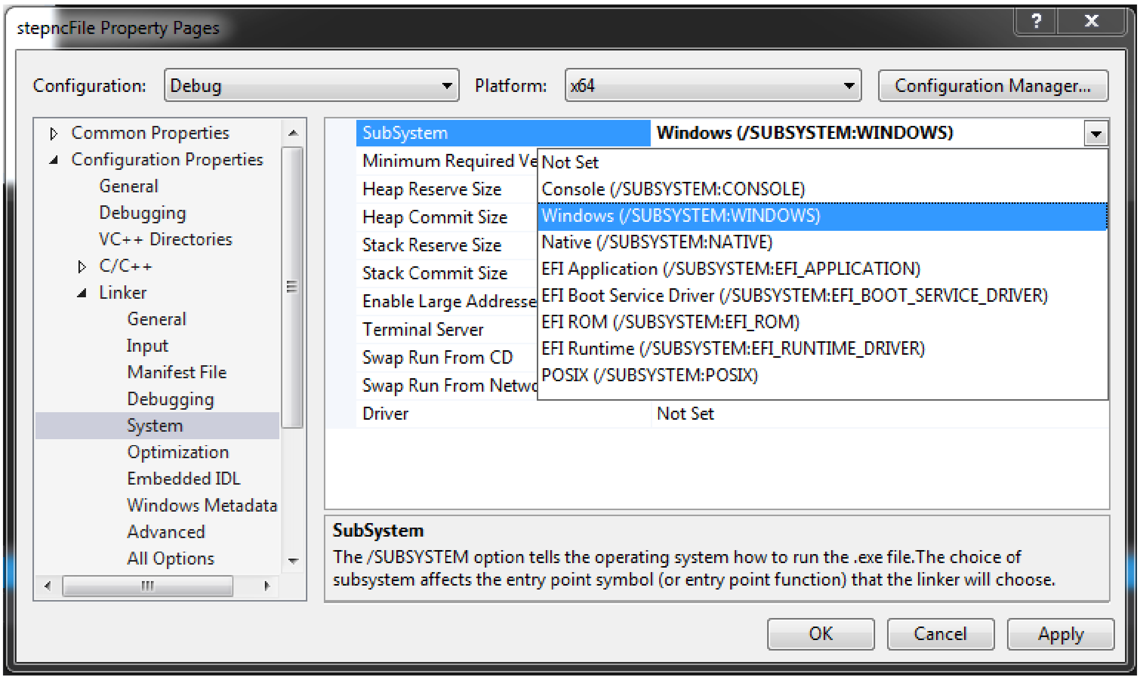
Select **New** from the **Active solution platform** menu and choose the **x64** platform. Press on **OK** and close the **Configuration Manager** box.



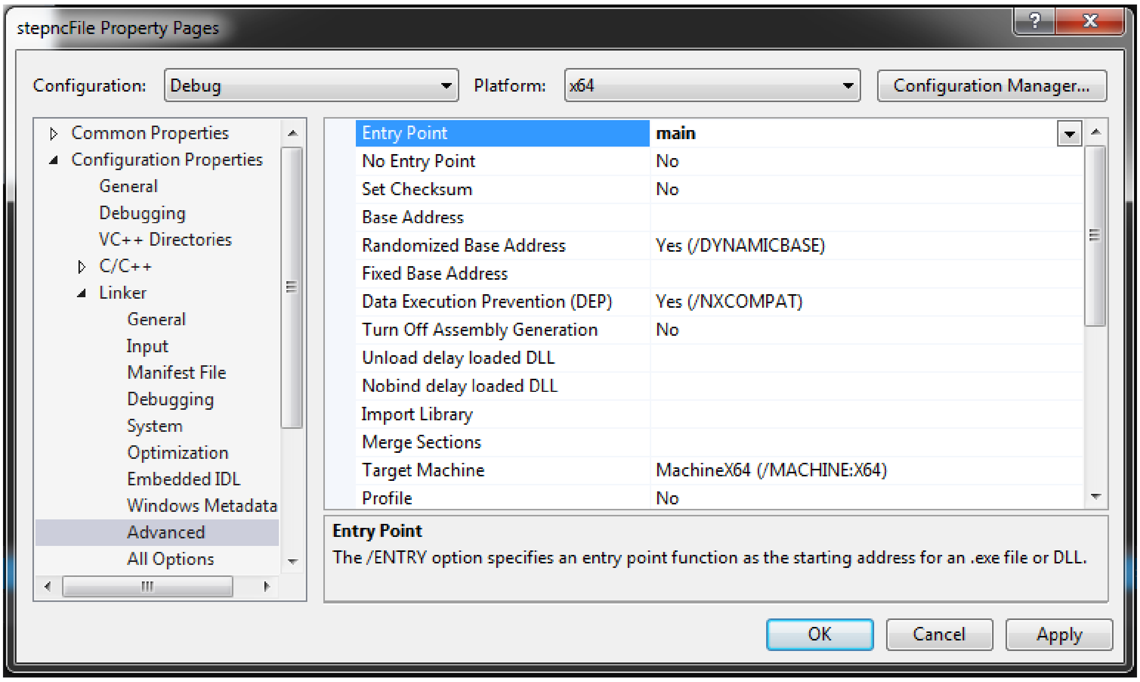
Continuing in the **Property Pages**, in the **Configuration Properties** drop-down list, go to **General** and select **Common Language Runtime Support (/clr)** from the menu shown in the figure.



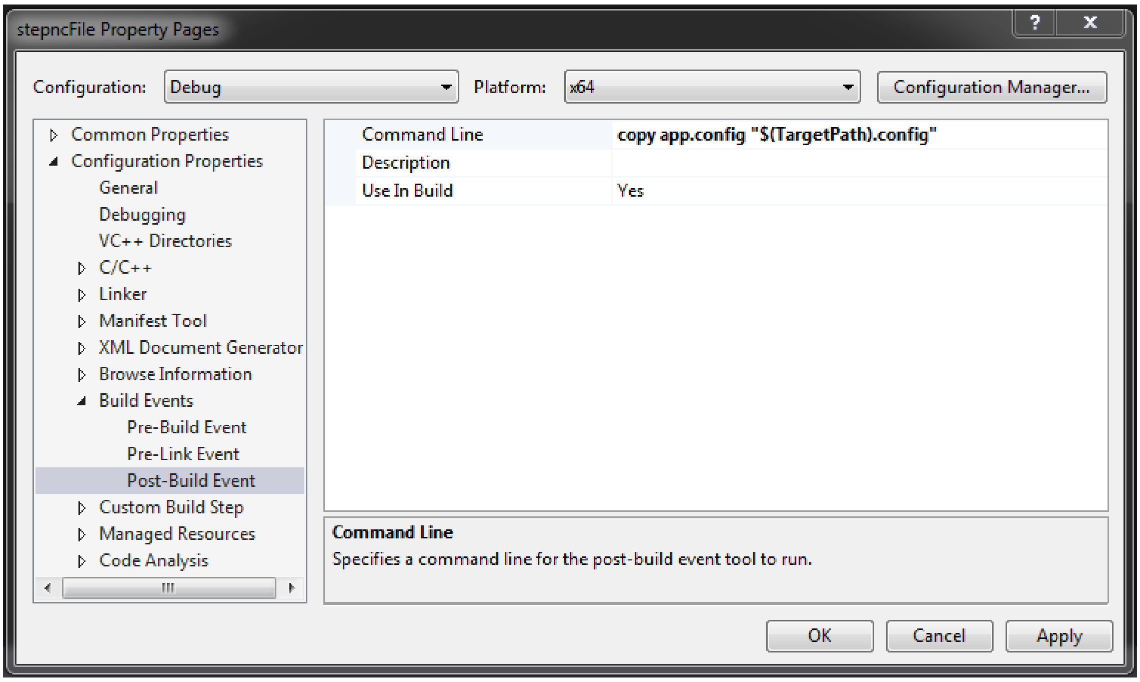
In the path **Linker->System->SubSystem** select **Windows (/SUBSYSTEM:WINDOWS)** for execution environment of Windows (GUI) application.



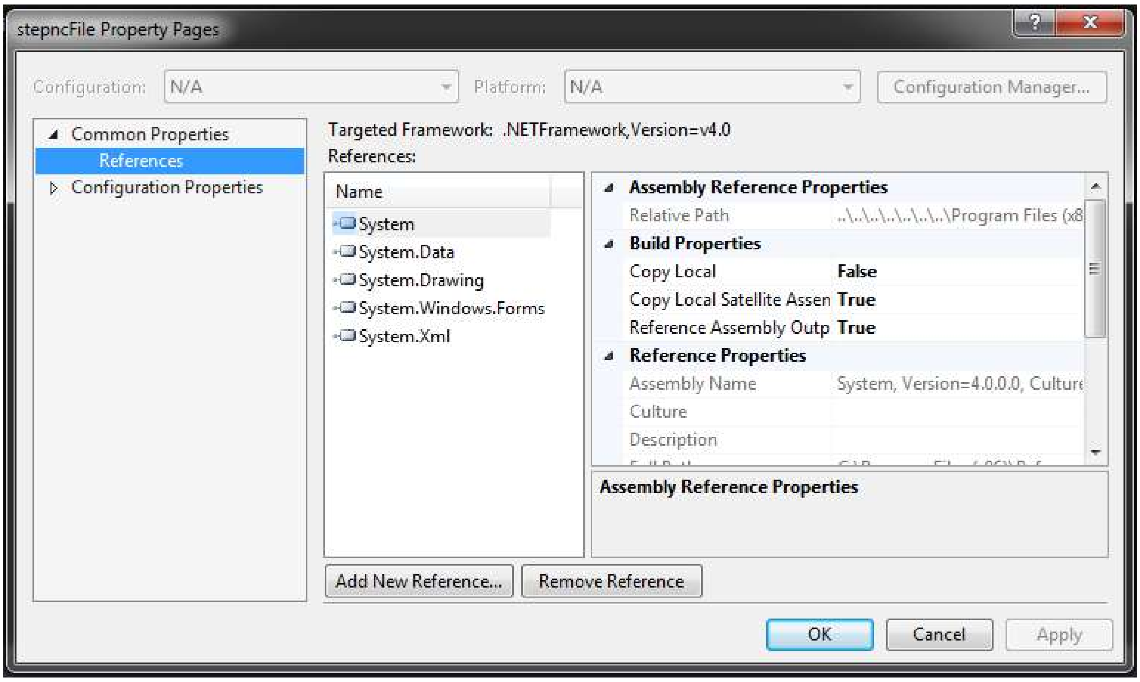
Define the starting address of the project as “main” function in **Linker->Advanced->Entry Point**.



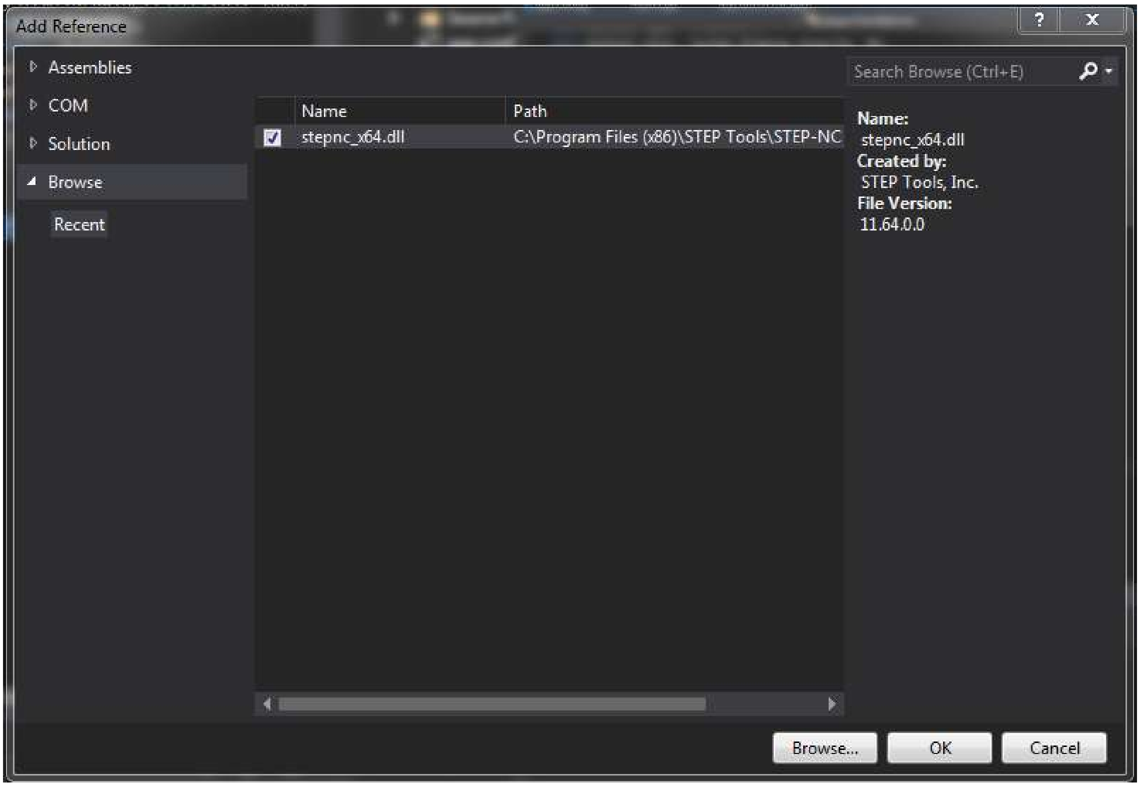
Specify a post-build events for the **Build Events** page by typing the sentence **copy app.config “($TargetPath).config”** in the **Command Line** edit box.



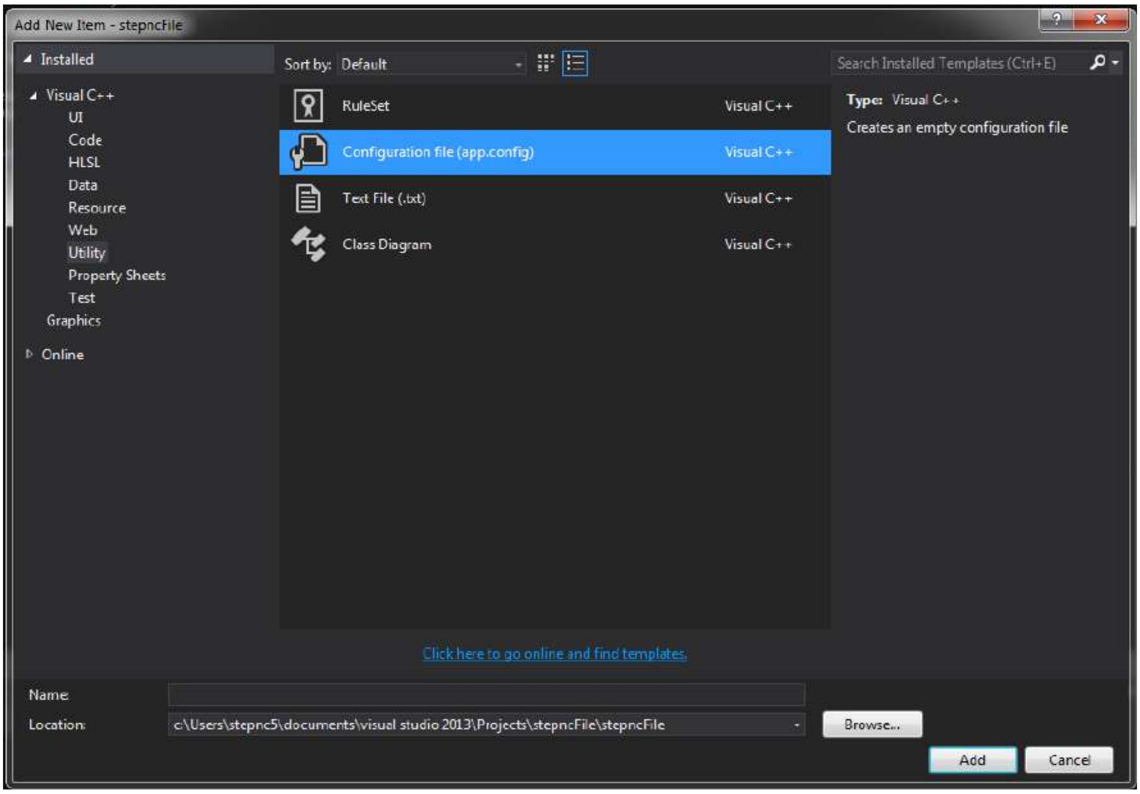
An important step is to add the **stepnc.dll** as within the reference from the project to use its functions in the building the STEP-NC data. You can add that stepnc.dll accessing by **Common Properties->References** and clicking on **Add New Reference.**



The **Browser** will allow you to access the **stepnc.dll** through from the aforementioned STEP-NC Machine directory.



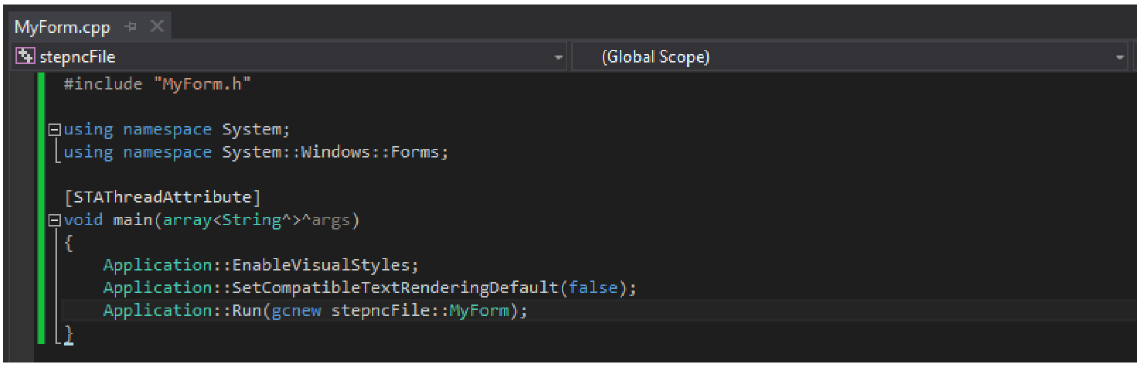
You will also need to create an **.xml configuration file** for the project. You can do it by adding a new item from C++ **Utility** menu, well as shown in the figure.



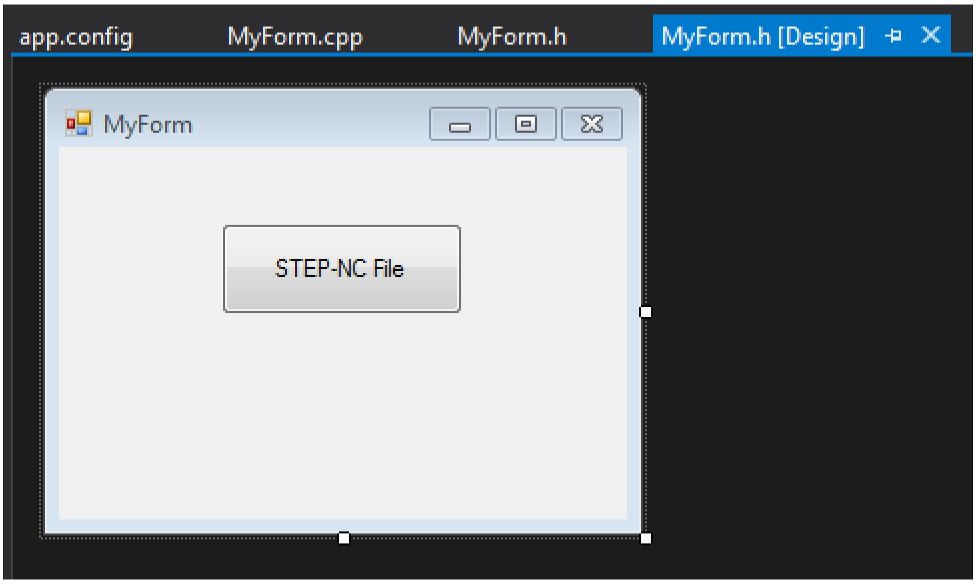
In the created **app.config** file type the following necessary statements:

```
<?xml version="1.0" encoding="utf-8" ?>
<configuration>
  <startup useLegacyV2RuntimeActivationPolicy="true">
    <supportedRuntime version="v4.0" sku=".NETFramework,Version=v4.5" />
  </startup>
</configuration>
```

In the **MyForm.cpp** file of the project place the following code necessary:



Add a button object into main form as seen in the figure.



In the **MyForm.h** file, just inside the definition code part of the object button, you will begin to develop your STEP-NC machining part program. Below is a code template to generate a trivial STEP-NC machining program file using methods of stepnc.dll that are based on the APT CL file standard.

```
app.config    MyForm.h    MyForm.cpp    MyForm.h [Design]
stepncFile                                stepncFile::MyForm

        }
#pragma endregion
    private: System::Void button1_Click(System::Object^  sender, System::EventArgs^  e) {

        STEPNCLib::AptStepMaker ^apt = gcnew STEPNCLib::AptStepMaker();

        //creating a machining program
        apt->PartNo("test part");
        //defining tool
        apt->DefineTool(10.0, 2.5, 1.0, 2.0, 3.0, 4.0, 5.0);
        apt->LoadTool(1);
        //set cutting parameters
        apt->Feedrate(200);
        apt->SpindleSpeed(1500);
        apt->CoolantOn();
        //workingstep
        apt->Workingstep("WS-1");
        //simple toolpath
        apt->GoToXYZ("P-1", 10.0, 10.0, 0.0);
        apt->GoToXYZ("P-2", 30.0, 10.0, 0.0);
        apt->GoToXYZ("P-3", 30.0, 30.0, 0.0);
        apt->GoToXYZ("P-4", 10.0, 30.0, 0.0);
        apt->GoToXYZ("P-5", 10.0, 10.0, 0.0);
        //save STEP-NC program as P21 file
        apt->SaveAsP21("test program");
    }
    };
}
```

Firstly, you define an object *apt* belonging to *AptStepMaker* class included in the *STEPNCLib* library of stepnc.dll.

Subsequently, create a STEP-NC program session through the *PartNo* method with the program name as input parameter.

DefineTool will allow you to define a tool, where the first input parameter refers to tool diameter. That tool can be load by using *LoadTool* specifying its number.

You can set cutting parameters such as feedrate, spindle speed and coolan activation.

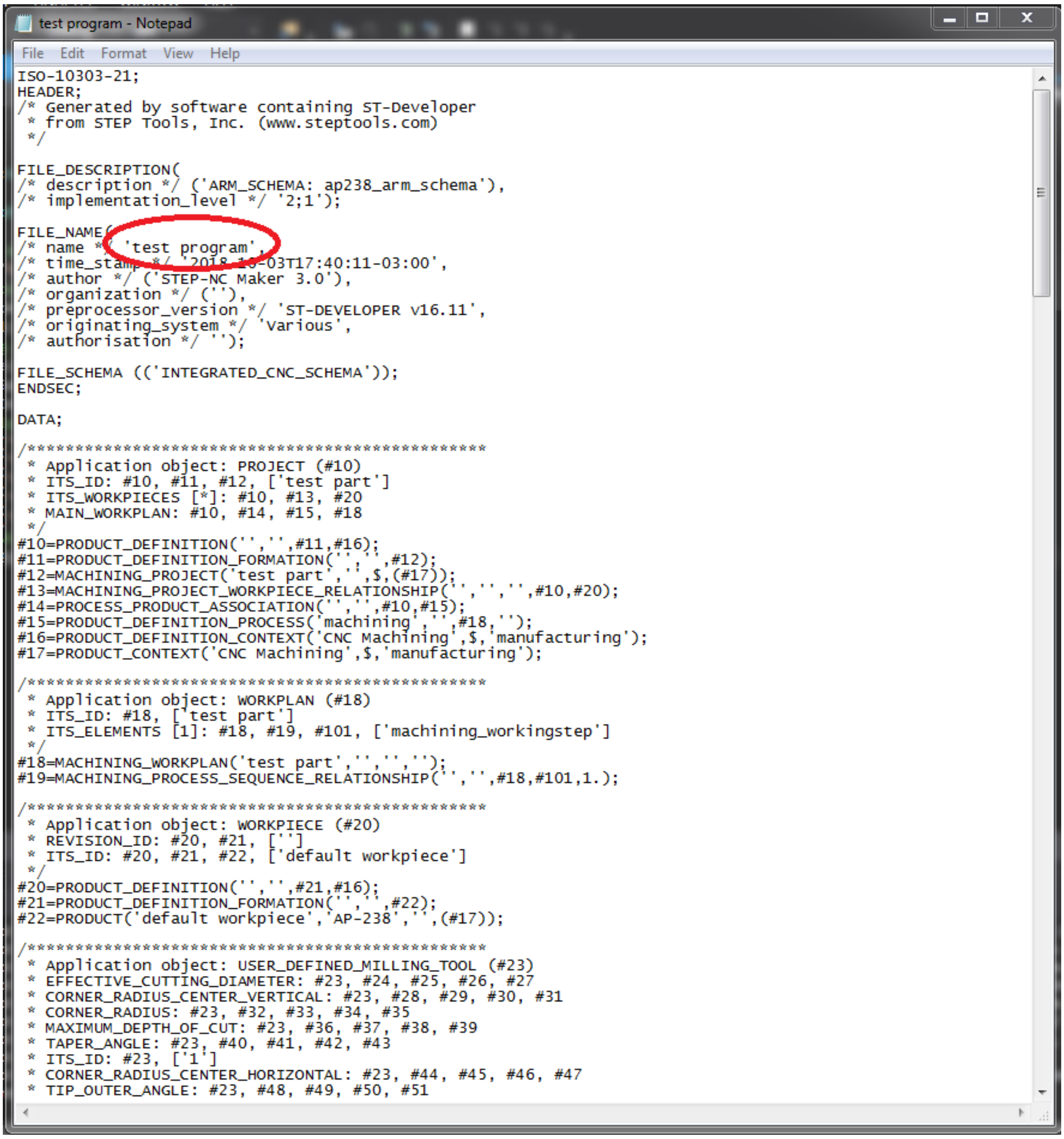
Workingstep method will allow you create a workingstep within the machining program passing its label as input parameter.

With *GoToXYZ* you can create toolpath specifying the XYZ Cartesian point.

Finally, the STEP-NC data file in P21 format can be generated through the *SaveAsP21* method with the file name as input parameter.

The file is saved in your project directory. A fragments of the STEP-NC program generated with the used code is shown in the figures.

Nice!



```
ISO-10303-21;
HEADER;
/* Generated by software containing ST-Developer
 * from STEP Tools, Inc. (www.steptools.com)
 */

FILE_DESCRIPTION(
/* description */ ('ARM_SCHEMA: ap238_arm_schema'),
/* implementation_level */ '2;1');

FILE_NAME(
/* name */ 'test program',
/* time_stamp */ '2018-10-03T17:40:11-03:00',
/* author */ ('STEP-NC Maker 3.0'),
/* organization */ (''),
/* preprocessor_version */ 'ST-DEVELOPER v16.11',
/* originating_system */ 'Various',
/* authorisation */ '');

FILE_SCHEMA (('INTEGRATED_CNC_SCHEMA'));
ENDSEC;

DATA;

/*****************************************************
 * Application object: PROJECT (#10)
 * ITS_ID: #10, #11, #12, ['test part']
 * ITS_WORKPIECES [*]: #10, #13, #20
 * MAIN_WORKPLAN: #10, #14, #15, #18
 */
#10=PRODUCT_DEFINITION('','',#11,#16);
#11=PRODUCT_DEFINITION_FORMATION('','',#12);
#12=MACHINING_PROJECT('test part','',$,(#17));
#13=MACHINING_PROJECT_WORKPIECE_RELATIONSHIP('','','',#10,#20);
#14=PROCESS_PRODUCT_ASSOCIATION('','',#10,#15);
#15=PRODUCT_DEFINITION_PROCESS('machining','',#18,'');
#16=PRODUCT_DEFINITION_CONTEXT('CNC Machining',$,'manufacturing');
#17=PRODUCT_CONTEXT('CNC Machining',$,'manufacturing');

/*****************************************************
 * Application object: WORKPLAN (#18)
 * ITS_ID: #18, ['test part']
 * ITS_ELEMENTS [1]: #18, #19, #101, ['machining_workingstep']
 */
#18=MACHINING_WORKPLAN('test part','','','');
#19=MACHINING_PROCESS_SEQUENCE_RELATIONSHIP('','',#18,#101,1.);

/*****************************************************
 * Application object: WORKPIECE (#20)
 * REVISION_ID: #20, #21, ['']
 * ITS_ID: #20, #21, #22, ['default workpiece']
 */
#20=PRODUCT_DEFINITION('','',#21,#16);
#21=PRODUCT_DEFINITION_FORMATION('','',#22);
#22=PRODUCT('default workpiece','AP-238','',(#17));

/*****************************************************
 * Application object: USER_DEFINED_MILLING_TOOL (#23)
 * EFFECTIVE_CUTTING_DIAMETER: #23, #24, #25, #26, #27
 * CORNER_RADIUS_CENTER_VERTICAL: #23, #28, #29, #30, #31
 * CORNER_RADIUS: #23, #32, #33, #34, #35
 * MAXIMUM_DEPTH_OF_CUT: #23, #36, #37, #38, #39
 * TAPER_ANGLE: #23, #40, #41, #42, #43
 * ITS_ID: #23, ['1']
 * CORNER_RADIUS_CENTER_HORIZONTAL: #23, #44, #45, #46, #47
 * TIP_OUTER_ANGLE: #23, #48, #49, #50, #51
```

```
#77=ACTION_PROPERTY_REPRESENTATION('','milling',#76,#78);
#78=REPRESENTATION('constant',(#79),#57);
#79=DESCRIPTIVE_REPRESENTATION_ITEM('constant','coolant on');

/******************************************************
 * Application object: MACHINING_WORKINGSTEP (#80)
 * ITS_ID: #80, ['WS-1 WS 1']
 * ITS_OPERATION: #80, #81, #124
 * ITS_FEATURE: #80, #82, #83, #84, #85, #107
 */
#80=MACHINING_WORKINGSTEP('WS-1 WS 1','machining','','');
#81=MACHINING_OPERATION_RELATIONSHIP('','machining',#80,#124);
#82=MACHINING_FEATURE_RELATIONSHIP('','machining',#80,#83);
#83=MACHINING_FEATURE_PROCESS('','machining','','');
#84=PROPERTY_PROCESS('machining','machining',#83,'');
#85=PROCESS_PROPERTY_ASSOCIATION('','machining',#84,#107);

/******************************************************
 * Application object: MILLING_TECHNOLOGY (#86)
 * SPINDLE: #86, #87, #88, #89, #90
 * FEEDRATE: #86, #91, #92, #93, #94
 */
#86=MACHINING_TECHNOLOGY('','milling','','');
#87=ACTION_PROPERTY('spindle','milling',#86);
#88=ACTION_PROPERTY_REPRESENTATION('rotational speed','milling',#87,#89);
#89=MACHINING_SPINDLE_SPEED_REPRESENTATION('spindle speed',(#90),#57);
#90=MEASURE_REPRESENTATION_ITEM('rotational speed',NUMERIC_MEASURE(1500.),
#95);
#91=ACTION_PROPERTY('feedrate','milling',#86);
#92=ACTION_PROPERTY_REPRESENTATION('feed speed','milling',#91,#93);
#93=MACHINING_FEED_SPEED_REPRESENTATION('feed speed',(#94),#57);
#94=MEASURE_REPRESENTATION_ITEM('feed speed',NUMERIC_MEASURE(200.),#104);
#95=DERIVED_UNIT((#96,#99));
#96=DERIVED_UNIT_ELEMENT(#97,1.);
#97=CONTEXT_DEPENDENT_UNIT(#98,'revolution');
#98=DIMENSIONAL_EXPONENTS(0.,0.,0.,0.,0.,0.,0.);
#99=DERIVED_UNIT_ELEMENT(#100,-1.);
#100=(
CONVERSION_BASED_UNIT('minute',#102)
NAMED_UNIT(#101)
TIME_UNIT()
);
```

```
/******************************************************
 * Application object: FREEFORM_OPERATION (#124)
 * ITS_TECHNOLOGY: #124, #125, #86
 * ITS_TOOLPATH [1]: #124, #126, #128
 * ITS_ID: #124, ['P-1']
 * ITS_TOOL: #124, #23
 * ITS_MACHINE_FUNCTIONS: #124, #127, #115
 */
#124=FREEFORM_MILLING_OPERATION('P-1','','','');
#125=MACHINING_TECHNOLOGY_RELATIONSHIP('','',#124,#86);
#126=MACHINING_TOOLPATH_SEQUENCE_RELATIONSHIP('','',#124,#128,1.);
#127=MACHINING_FUNCTIONS_RELATIONSHIP('','',#124,#115);

/******************************************************
 * Application object: CUTTER_LOCATION_TRAJECTORY (#128)
 * BASICCURVE: #128, #129, #130, #131, #132
 * ITS_ID: #128, ['P-1 WS 1 TP 1']
 * ITS_TECHNOLOGY: #128, #133, #86
 */
#128=MACHINING_TOOLPATH('P-1 WS 1 TP 1','cutter location trajectory','',
'');
#129=ACTION_PROPERTY('basic curve','cutter location trajectory',#128);
#130=ACTION_PROPERTY_REPRESENTATION('','cutter location trajectory',#129,
#131);
#131=REPRESENTATION('',(#132),#57);
#132=POLYLINE('',(#134,#135,#136,#137,#138));
#133=MACHINING_TECHNOLOGY_RELATIONSHIP('','cutter location trajectory',
#128,#86);
#134=CARTESIAN_POINT('',(10.,10.,0.));
#135=CARTESIAN_POINT('',(30.,10.,0.));
#136=CARTESIAN_POINT('',(30.,30.,0.));
#137=CARTESIAN_POINT('',(10.,30.,0.));
#138=CARTESIAN_POINT('',(10.,10.,0.));

/******************************************************
 * END OF APPLICATION OBJECT DESCRIPTIONS
 */
#139=NAME_ATTRIBUTE('revolution/minute',#95);
#140=NAME_ATTRIBUTE('inch/minute',#104);
ENDSEC;
END-ISO-10303-21;
```

Simulation in STEP-NC Machine software was successful. The generated toolpath is associated to WS-1 workingstep instantiated in code.

Note that this program can be enriched with more machining data by using the classes and methods of the STEPNCLib library.